Theses and Dissertations   1. Thesis and Dissertation Collection, all items

1986-09

Spread spectrum systems: a point of view between technology and management.

Katopodis, Thomas P.

http://hdl.handle.net/10945/22116

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

SPREAD SPECTRUM SYSTEMS:
A POINT OF VIEW BETWEEN
TECHNOLOGY AND MANAGEMENT

Thomas P. Katapodis

September 1986

Thesis Advisor: Thomas J. Brown

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

1. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS			
2. SECURITY CLASSIFICATION AUTHORITY		3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited			
2. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4 PERFORMING ORGANIZATION REPORT NUMBER(S)		5 MONITORING ORGANIZATION REPORT NUMBER(S)			
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School	6b OFFICE SYMBOL (If applicable) 62	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School			
6c ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000		7b. ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification) SPREAD SPECTRUM SYSTEMS: A POINT OF VIEW BETWEEN TECHNOLOGY AND MANAGEMENT (UNCLASSIFIED)

12 PERSONAL AUTHOR(S)
Atopodis, Thomas P.

13a TYPE OF REPORT Master's Thesis	13b TIME COVERED FROM ____ TO ____	14 DATE OF REPORT (Year, Month, Day) 1986 September	15 PAGE COUNT 112

16 SUPPLEMENTARY NOTATION

COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Spread Spectrum, Direct Sequence Systems, Frequency Hopping System, Spread Spectrum Multiple Access, Chirp, Spectrum Management, Hybrid

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Only recently has technology come to the point of making circuitry and systems reasonably small, reliable, and inexpensive so as to enable practical implementations of spread spectrum (SS) concepts. Viewed as a motivating force encouraging the growth of the field, this recently developed capability for practical SS systems must be reinforced by the additional pressure of more and greater demands being made on communications systems than ever before. Increased message traffic from a higher number of users is creating a need for protection of information from interference and eavesdropping. As a result of these two major forces, the availability of systems and components coupled with the need for improved communications, the field of SS communications has rapidly emerged in recent years as a major thrust in the technical community. This thesis provides a summary of the principles upon which SS systems have developed and the progress of

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL Thomas J. Brown	22b TELEPHONE (Include Area Code) 408-646-2772	22c OFFICE SYMBOL 62Bb

DD FORM 1473, 84 MAR   83 APR edition may be used until exhausted   SECURITY CLASSIFICATION OF THIS PAGE
                              All other editions are obsolete

Block 19   ABSTRACT (cont'd)

frequency management involving spread spectrum systems.

2

Spread Spectrum Systems:
A Point of View Between Technology and Management

by

Thomas P. Katopodis
Lieutenant Commander, Hellenic Navy
B.S., Hellenic Naval Academy, 1970

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN TELECOMMUNICATIONS SYSTEMS MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 1986

ABSTRACT

Only recently has technology come to the point of making circuitry and systems reasonably small, reliable, and inexpensive so as to enable practical implementations of spread spectrum (SS) concepts. Viewed as a motivating force encouraging the growth of the field, this recently developed capability for practical SS systems must be reinforced by the additional pressure of more and greater demands being made on communications systems than ever before. Increased message traffic from a higher number of users is creating a need for protection of information from interference and eavesdropping. As a result of these two major forces, the availability of systems and components coupled with the need for improved communications, the field of SS communications has rapidly emerged in recent years as a major thrust in the technical community. This thesis provides a summary of the principles upon which SS systems have developed and the progress of frequency management involving spread spectrum systems.

TABLE OF CONTENTS

LIST OF TABLES

7

LIST OF FIGURES

ACKNOWLEDGEMENTS

The writer wishes to express his gratitude to the various members of the Naval Postgraduate School faculty, staff, and student body whose assistance and encouragement contributed to the success of this thesis investigation.

Also, a special thanks is extended to my thesis advisors, Professor Thomas J. Brown and Professor Paul M. Carrick, for guidance and support.

Finally, but not least, I want to thank my wife Katy who made studying easier and our stay in Monterey very pleasant.

I. INTRODUCTION

A. BACKGROUND

As a result of advances in communication theory and systems technology in the last decade the use of telecommunication services has rapidly multiplied, placing new demands on the radio spectrum. This growth in the radio frequency spectrum usage has resulted in congestion, and the situation is getting steadily worse. Serious consequences await agencies and nations which do not maintain an active, progressive program to protect their existing operations and to provide for accommodation of new planned systems. Competition for this vital spectrum resource has already reached the point where communications navigation and surveillance systems in use today are threatened by encroachment from other spectrum users. In addition, any plans to introduce new systems will confront spectrum availability as a formidable problem. Also, in the past years, there has been an increasing realization that we are faced with a rapidly growing problem throughout the world of attaining effective and efficient use of the radio spectrum. [Ref. 1]

Spectrum demands have been met traditionally by simple administrative techniques because technology has kept increasing the amount of spectrum space available and reducing necessary bandwidth. Recently, the growth of the usable spectrum has slowed while the demand placed upon it has grown exponentially. This turn of events has induced spectrum managers to consider different approaches to frequency allocation and assignment.

10

Given that a band must be used by more than one justifiable user, the problem is to determine the specific criteria which can be applied to two or more users on mutually cooperative rather than a mutually exclusive basis for more effective use of the spectrum.

To overcome the problem the concept of spread spectrum communication systems has been advocated.

Most of the concepts of spread spectrum systems have been understood for many years, but the components and techniques for building systems capable of reliable operation have been available for a much shorter time. J. P. Costas concluded in 1959 that ''for congested-band operation, broadband systems appear to offer a more orderly approach to the problem and a potentially higher average traffic volume than narrow-band systems.'' [Ref. 2]. At that time, however, transistors and other components were not available to build a reliable, reasonably sized spread spectrum system. Today, components have advanced to the point at which large parts of a spread spectrum system can be contained in a single integrated circuit. A code generator, for instance, which even in 1967 would have required at least 100 discrete transistors, can easily be incorporated in a single small package only slightly larger than one of the transistors. In the future a complete subsystem may well be reduced to one similarly small package. The point is that the use of spread spectrum techniques is no longer constrained by constituent electronic components, within limits.

B. PURPOSE

This thesis will be an investigation of the principles upon which spread spectrum systems have developed. Also, this thesis is to provide an assessment of the frequency

11

bands that might be used by spread spectrum systems, with explanations of the constraints due to both electromagnetic compatibility considerations and frequency allocation regulations. Also, this thesis will provide an assessment of the spread spectrum systems performance analysis. Finally, it will recommend general rules and procedures required to allow the utilization of the spread spectrum systems while simultaneously protecting authorized conventional systems to the maximum extent possible.

C. APPROACH

This thesis begins with this brief introduction and then is divided into five basic areas. Chapter Two explores spectrum management allocation processes and problems. Chapter Three looks at spread spectrum systems with emphasis on the different techniques and how their application affects spectrum management. Chapter Four assesses the performance analysis of the spread spectrum systems. Chapter Five assesses the frequency bands that spread spectrum may possibly use and their effects on spectrum utilization. Finally, Chapter Six explores possible spectrum allocation alternatives using spread spectrum systems.

II. SPECTRUM MANAGEMENT

A. INTRODUCTION

The electromagnetic spectrum is an intangible resource which is available to everyone--at least in theory. Unfortunately, it is also a limited resource since only a very small portion of the spectrum can be used for any given purpose within the bounds of present technology. The radio spectrum is a resource which man has exploited since about 1900 to advance his safety and welfare and to provide entertainment. Radio spectrum is somewhat different from other resources, such as minerals, water, fossils, fuels, and so on, in that we must be concerned with the following characteristics:

1. This resource is used and not consumed. It's being wasted when it's not being used. Administration and management of the resource requires allocation by segments and other means.

2. The resource has dimensions of space, time, and frequency, and all three are interrelated.

3. It is an international resource, available to all.

4. The resource is wasted when it's assigned to do tasks that can be done as easily or better in other ways. The resource is wasted when the parameters are not correctly applied to a task.

5. The resource is subject to pollution, and that's going to be one of the major subjects today. [Ref.1]

The demand for the use of the radio frequency spectrum has grown steadily since 1935. The incentive for this growth in the number of spectrum users and, consequently, the number of separate frequencies in use can be linked to the growth in per capita income, the changes in taste, and the levels in population. Like other natural resources the

13

demand for spectrum has produced an increase in the available supply of spectrum in two ways:

1. At the extensive margin.
2. At the intensive margin.

First, the technology to operate at higher frequencies has expanded the quality of spectrum, an increase in supply at the extensive margin. Second, technology has permitted closer channel spacing, e.g., the utilization of more channels per frequency band. This has been done through the development of technologically improved transmitters, receivers, antennas, etc. These technological improvements facilitate close channel spacing because of narrower frequency tolerances. This is an increase in the supply of spectrum at the intensive margin. The supply of spectrum is, therefore, largely determined by technology, but management and economics also play important roles in determining the supply of spectrum. Technology may increase the supply of spectrum, but management of the spectrum improves its use in time, space, and frequency. Spectrum management is concerned with the problem of the spectral dimensions of time,— space, and frequency. Signals transmitted on a specific frequency occupy all three spatial dimensions. The degree to which the physical space through which the signals pass is in fact occupied depends upon the radiated power. Extreme power will so saturate physical space so as to prevent any other signal from being intelligibly received within it. To illustrate, two spectrum users may simultaneously transmit on the same frequency if sufficiently geographically separate. Because of their geographic separation, they occupy different spectrum in the spatial sense. If, however, they are not geographically separated and transmit on the same frequency and with the same power, but at different moments in time, they occupy different spectrum in a temporal sense.

14

However, if they transmit with the same power at the same time and are not geographically separated, they occupy the same spectrum.

Economics plays an important role in determining the usable supply of spectrum. The cost of the technology required to utilize higher frequencies or to utilize more closely spaced frequencies may limit the economic usability of the supply of spectrum. Thus, the high cost of technology to utilize frequencies effectively limits the supply available for apportionment among users.

In essence, technology provides the physical supply of spectrum, management concerns itself with the apportionment of that supply, and economics measures the economic usability of the supply of spectrum. [Ref. 3]

After that many countries, like the United States, are literally running out of space to accommodate all who would like to use the resource. This problem is compounded by the fact that international and national spectrum management responsibilities are fragmented among many government and nongovernment agencies, committees, commissions, advisory boards, and user groups. Because of this fragmentation, no single agengy has the total administrative, engineering, and information capabilities necessary to provide optimum spectrum management on a nationwide basis. During the past decades, extensive research, development, and analysis have been conducted in the spectrum management field which provide the technical basis for solutions to this problem. [Ref. 4]

B.   SPECTRUM ALLOCATION PROCESS
Two important aspects of resource apportionment are assignment and allocation. Allocation may be thought of in two ways. First, allocation may be viewed as the

15

designation of a band of frequencies to a specific telecommunications service such as maritime mobile, fixed broadcasting, aeronautical navigation, amateur, etc. This first view of allocation implies the existence of no specific spectrum user or constraint of particular frequencies to a particular geographic area. Second, allocation may be viewed as the designation of a band of frequencies and a specific service application to a given user or particular geographic area.

On the other hand, assignment is defined as the designation of a specific frequency within an allocation for a specific user of communications electronics equipment. Assignment implies some property rights to the user of that frequency to the mutual exclusion of other users. [Ref. 5]

A distinction between assignment and allocation is that allocations are made at the international level while assignments are made by individual nations. Assignments are designed to the made in accordance with a national allocation plan which is a subset of the international allocation plan. Spread spectrum frequency management involves the allocation and assignment of spread spectrum frequencies. The term management, used in this sense, is the attempt to control the utilization of the spectrum in order to obtain the greatest benefit for the greatest number of people.

Our use of the spectrum began with very crude equipment (by today's standards) for communications by telegraph between ships at sea and with the shore. Even this very early use brought out the next major point with regard to the spectrum, which is that it is an international resource and can be used efficiently only in accord with international agreements on standards and procedures, and frequency assignments to services. The early use by ships

16

led to an agreement reached in Berlin in 1903 on procedures for handling messages. Another meeting in Berlin in 1906 adopted the first regulations concerning the use of frequencies (wavelengths in those days) which went into effect in most countries in 1908. These beginning efforts at international cooperation were extensively concerned with radio telegraph procedures which became entrusted to the Bureau of the International Telegraph Union. (This Union had been established in 1865 to develop cooperation in wire telegraph services primarily throughout Europe.) From this modest beginning grew the extensive present organization of the International Telecommunication Union (ITU), now a Specialized Agency of the United Nations. [Ref. 1]

The ITU, like its predecessors, is a voluntary association of independent countries formed to enhance the conduct of international communications. It is voluntary in the sense that nations could confine their communications within their own national borders, but because of commercial and political reasons, they choose not to do so. The representatives of ITU member nations meet periodically and draw up, by mutual agreement, rules, regulations, and recommendations for the conduct of telecommunication services. The ITU consists of various technical committees and working groups. Figure 2.1 shows the ITU organization structure.

The history of international communications organizations has been divided into three periods: 1906-1957, echnological, 1957-1971, Transition to Political, and 1971-Present, Political. [Ref. 6]

17

```
                    ┌─────────────────────┐
                    │   PLENIPOTENTIARY   │
                    │     CONFERENCE      │
                    └─────────────────────┘
                              │
                    ┌─────────────────────┐
                    │   ADMINISTRATIVE    │
                    │      COUNCIL        │
                    └─────────────────────┘
```

Figure caption / diagram text:

PLENIPOTENTIARY CONFERENCE

ADMINISTRATIVE COUNCIL

WORLD ADMIN TELEGRAPH & TELEPHONE CONFERENCE

WORLD ADMIN RADIO CONFERENCE

CCITT PLENARY ASSEMBLY

GENERAL SECRETARIAT

INT'L FREQ REGISTRATION BOARD (IFRB)

SECRETARIAT

LABORATORY

SECRETARIAT

STUDY GROUPS

CCIR PLENARY ASSEMBLY

SECRETARIAT

STUDY GROUPS

[Ref. 3: p. 17]

Figure 2.1   ITU Structure

18

The earliest period was marked by decisions concerning the technical aspects of communications such as the adoption of a standard design telegraph key, a standard telegraph code, technical standards for transmitters to reduce frequency drift and interference, licensing of operators, interface equipment standards, and the allocation of frequencies to various services.

During the period 1957-1971, the World saw many former colonies gaining their independence and emerging as a bloc called the Lesser Developed Countries (LDC'S). The LDC'S have emerged as a significant political power which has used the United Nations as a venue for pushing their case for a greater share of technology, resources and capital. The LDC'S believe that these items have been monopolized by the industrial nations to the detriment of the LDC'S. In the telecommunications arena, for example, the equatorial countries have claimed that they are the controllers of a very important natural resource, the geostationary orbital position for satellites. The LDC'S perceive access to these systems and spectrum space as a source of revenue. The LDC'S see that the telecommunications systems of the developed nations have proved to be an economic resource for the developed nations. They, therefore, wish to do the same for themselves. The LDC'S, through bloc voting, have the power to gain access to these things on their own terms, i.e., frequencies utilized and technical/financial aid for telecommunication systems. As previously stated the LDC'S may attempt to use bloc voting tactics to dominate future radio conferences to gain allocations favorable to their interests.

However, to provide some semblance of order and for political reasons, goverment regulations specify the modulation type, bandwidth, and type of information that can be transmitted over designated frequency bands.

On an international basis, frequency assignments and technical standards are set by two committees:(see Fig.2.1) the International Telegraph and Telephone Consulative Committee (CCITT) and the International Radio Consultative Committee (CCIR). These committees function under the auspices of ITU. In the United States the Federal Communication Commission (FCC) regulates radio, telephone, television, and satellite transmission systems. The international frequency assignments are divided into subbands by the FCC to accomodate 70 categories of services and 9 million transmitters. Table I gives a general listing of frequency bands, their common designations, typical propagation conditions, and typical services assigned to these bands. A look at Table I shows that frequencies have differing characteristics. Therefore, some are more suited to one radio service than another. For example, high frequencies (3-30 MHz) are useful for low capacity, worldwide radio communications,but are not useful for high capacity circuits or for television. Ideally, frequencies should be allocated to services based on their characteristics.

As the value of radio communications became more apparent, the demand for additional services (e.g. radiotelephone) and expansion of existing services grew. The current political - economic climate hinders the allocation/reallocation of frequencies based on technology, but demands the careful assessment of the political and economic implications of the allocations. The ITU member nations, through mutual agreement, allocate frequencies to services by goegraphic regions. The ITU member delegations make frequency allocation recommendations based on technical considerations. But the actual allocations are made as a result of the political, technical, and economic justifications presented by these same member nations.

TABLE I

FREQUENCY BANDS [Ref. 7]

Frequency Bands	Designation	Propagation Characteristics	Typical Uses
3-30 KHz	Very low Frequency (VLF)	Ground Wave, low attenuation day and night, high atmospheric noise level	Long-range navigation, submarine communication
30-300 KHz	Low frequency (LF)	Similar to VLF, slightly less reliable, absorption in daytime.	Long-range navigation and marine communication, radiobeacons
300-3000 KHz	Medium frequency (MF)	Ground wave and night skywave, attenuation low at night and high in day, atmospheric noise.	Maritime radio directionfinding, and emergency frequencies, AM broadcasting.
3-30 MHz	High frequency (HF)	Ionspheric reflection varies with time of day, season and frequency, low atmospheric noise at 30 MHz.	Amateur radio, international broadcasting, military communication, long distance aircraft and ship communication, telephone, telegraph, facsimile.
30-300 MHz	Very high frequency (VHF)	Nearly line-of-sight propagation with scattering due to temperature inversions, cosmic noise.	VHF television, FM two-way radio, AM aircraft communication, aircraft navigational aids.

0.3-3 GHz	Ultra high frequency (UHF)	Line-of-sight propagation, cosmic noise.	UHF television, navigation aids radar, microwave links.

	Old	New
0.5-1.0	VHF	C
1.0-2.0	L	D
2.0-3.0	S	E

3-30 GHz	Super high frequency (SHF)	Line-of-sight propagation, rainfall attenuation above 10 GHz, atmospheric attenuation due to oxygen and water vapor, high water vapor absorption at 22.2 GHz.	Satellite communication, radar microwave links.

	Old	New
3.0-4.0	S	F
4.0-6.0	C	G
6.0-8.0	C	H
8.0-10.0	X	I
10.0-12.4	X	J
12.4-18.0	Kn	J
18.0-20.0	K	J
20.0-26.5	K	K
26.5-40.0	Ka	K

30-300 GHz	Extremely high frequency (EHF)	Same, high water vapor absorption at 183 GHz and oxygen absorption at 60 and 119 GHz.	Radar, satellite, experimental.
10^3-10^7 GHz	Infrared visible light, and ultraviolet.	Line-of-sight propagation.	Optical communications.

C.   NATURE OF THE PROBLEM

  1.   Introduction

        Electromagnetic compatibility is a two-way street.
The users of the electromagnetic environment must share the
same resource and ''get along'' with each other. This was
not much of a problem in the past when frequencies were
plentiful, and even exclusive use of frequencies was
commonplace. However, the spectrum is now crowded, and
performance thresholds are likely to be determined by the
level of interfering signals, rather than by ambient noise.
As a matter of fact, it is only when operational service
ranges   reach   the   limitations   imposed   by marginal
interference rather than noise, that the spectrum is
considered to be used to full capacity.

        This   does   not   imply   that   the   spectrum   is
necessarily being used efficiently under marginal
interference conditions. It does   mean that with the
equipment in use and under the conditions of their use,
interference defines the limit on the amount of service
which can be accommodated. Thus, if we are to learn to
study and predict interference conditions accurately enough
to determine when interference becomes an unacceptable
threat.

        Exlusive frequencies and block frequency allotments
to user groups are luxuries spectrum managers can no longer
afford. However, the alternatives require the support of
studies and models in more detail and with   higher
engineering precision than can be accomplished with the
staffs, records, and technical capabilities now available.
[Ref. 4]

        What   is   the   nature   of   the electromagnetic
compatibility problem in a dynamic and complex environment?
The density of planned use of the spectrum has forced
multiple reuse of each frequency and has resulted in

frequency assignments which admit to some potential for interference within acceptable limits. As the use of the spectrum has become more dense, the need for more efficient methods of using the spectrum, based upon the same kind of controlled marginal compatibility, has become evident.

Three primary factors determine the degree of compatibility in our electromagnetic environment:

1. The space, frequency and time density of spectrum use.
2. The characteristics of the equipments in use, and
3. The distribution of the available frequency resource among the users.

Any program that is designed to control electromagnetic compatibility must be able to understand and control these three factors. [Ref. 4]

2. Spectrum Management Problems

The present spectrum management agencies do not have the authority to manipulate these factors, except within rigidly limited frequency bands, and therefore cannot optimize spectrum utility. [Ref. 4: p. 17]. Further, these agencies are not likely to get the required authority unless they have the means at hand to guarantee acceptable service levels to users already committed to spectrum occupancy, while at the same time assuring reliable service to new users. This can be accomplished only through the use of analytical means which have a degree or credibility acceptable to both the spectrum users and the lawmakers who must protect each user's commitment to spectrum use and who, in addition, would have to sanction any basic change in the administration and management of the spectrum. Each proposed method for spectrum assignment must be developed, tested, measured, and proved to the satisfaction of all interested parties before it can achieve acceptance.

The resource we are interested in managing has the strange characteristic of being equally available everywhere, but subject to contamination at the point of use. The resource is only usable at any one place to the degree that the resource is not contaminated, or if it is contaminated, to the degree that the user can see through the contamination and still satisfy his requirements. The complex pattern of spectrum users creates on environment within which each user must live and function. If a spectrum manager is assigned the responsibility for improving the utility of the electromagnetic spectrum, he must first understand the existing environment, and then manipulate the future environment in such a manner as to improve spectrum usefulness.

The free users are chewing each other out, accusing each other of sloppy radiation, letting their signals get across boundaries, not doing an efficient and scientific job in packing the maximum amount of information into the smallest spectrum space, or, worse yet, not even using some allocated frequencies, while others are saying they need more. They still have a problem, they call it spectrum pollution, but they're worse off, they don't even know how bad it is nor how quickly it's getting worse.

The Federal Government of the United States is a large user of the radio spectrum resource for national security and defense, radio-navigation aids, air traffic control, law enforcement, conservation of natural resources, meteorological aids, scientific research, etc., for the benefit of 230 million people. The military services account for about two thirds of this Government use and, with the Federal Aviation Agency, account for about 80 percent of the total Government frequency assignments. Maritime radio-navigation aids, law enforcement, and conservation of national resources account for another 15 percent of such assignments. [Ref. 1]

The Department of Defense (DOD) may be the biggest user. We all appreciate that no modern defense organization can be effective unless it makes effective use of the potential that the spectrum affords. Most of the DOD users are very much like other users. The DOD relies on radio for controlling the operation of vehicles of all kinds. Maybe some others do take the opposite tack and ask why the DOD should have any uses that are different from those of others, if it's just another user, albeit big. I have four items that I think answer that question, and there are probably others. First, the DOD must always be vigilant and ready to respond. As an example, air defense radar must be on air not for just an 8-hour day, but for 24 hours a day. The second set of military requirements arises out of the facts of what we call ''electronic warfare.'' Usually we think of all users of the spectrum as trying to cooperate and live in harmony. It's true that everyone tries to get all the frequencies he can possibly use, but once he has them, I think he usually tries to live by the rules. But, during active warfare, attempts to use the spectrum for military purposes are quite likely to result in enemy attempts to interfere deliberately with its use, to jam it. Thus the DOD problem is multiplied manyfold, and the military find themselves requiring greater effective radiated power and many times the simple bandwidth that might be necessary just to transmit the information required, in order to establish a counter-countermeasures capability. A third complication arises primarily out of the second. This is the need for extensive security. Most basic electronic techniques sooner or later become well known. We can't hide the laws of nature. But, fortunately for militaries, there are usually many, many ways in which electronic devices can be used to perform useful military functions. As soon as one side learns just which technique

the opposition is using to perform a particular function, countermeasures can be quickly devised and equipment procured. Adequate security is hard to maintain in our open society, especially in an area like communications, or electronics, where a skilled intelligence man can extrapolate a long way from what seems like very simple clues. The fourth point is a very important one, and really thorny. It grows out of the need to prepare for war in time of peace. During hostilities, the urgency of winning establishes very high priority for military use of the spectrum, and many channels are made available then which in normal times are assigned to others, and quite rightly. But it's during such normal times that new designs must be proved, production equipment tested, military communications electronics concepts exercised and approved, optimums of equipments and techniques established, and, very important-ly, operators must be trained.

D. FUTURE ALLOCATION PROCESS

   1. Initial Approach

   With the presently available equipment and capabi-lities, the spectrum management could begin to assign frequencies to other classes of users in those bands which are set aside for the exclusive use of one user group, worldwide. This action would make additional frequencies available in geographical areas where one particular user group did not require and was not using its allotted frequ-encies. For example, frequencies set aside for the forestry service could be used by other services in areas where there are no forests. However, in order to achieve such a goal, while at the same time protecting the interests of those who already have investments in those bands, the spectrum manager would have to have much better frequency

assignment and utilization records than are presently available. Records, for example, would have to indicate more than technical characteristics, such as equipment type and antenna height. They would also have to specify various operational conditions, such as the limits of the area in which a mobile user could operate. With a knowledge of the location of each user of the spectrum in the region of a specific frequency assignment request and with the help of limited data processing, frequencies could be selected for which the nearest duplicate frequency authorizations would be outside the interference range. This procedure would be a relatively simple first step toward more efficient spectrum utilization.

    2.   <u>System Implementation</u>

        Electromagnetic compatibility is looked upon as a vast system problem containing both first - order and second-order solutions. It involves starting with the status quo, which is then subjected to the effects of both natural and man-made environments, applying standardized analysis techniques to arrive at potential short-range assignment solutions, possibly followed by long - range allocation changes, and finally, applying some means of feedback to close the loop, thereby updating the status quo in readiness for future problems. First-order solutions are required to minimize problems of direct co - channel interference. Second - order solutions are required to minimize interference resulting from intermodulation products, spurious, out-of-band radiation, noise, etc.

        The spectrum manager might next begin to build the tools of this trade. These would include:

    1.   Accurate spectrum authorization and usage records that would provide the basis for describing and understanding the electromagnetic environment.

2. The analytical tool which would allow him to predict interference in that known environment, and

3. The measuring and monitoring capability required to model and police spectrum utilization.

These would be the real tools of the trade in the era of the enlightened spectrum manager: records, measurement, enviromental synthesis, and analysis. Without this capability the spectrum manager could not really begin to analyze and understand spectrum usage problems in any detail. [Ref. 4]

The ultimate objective in the use of these tools would be to improve the accuracy with which the spectrum manager could predict interference so that he would be able to crowd users closer together without risking unacceptable interference. However, he would probably first use these tools for other purposes until he had gained enough confidence in them to warrant exposing the spectrum users to the dangers involved in prediction.His first application of the new capability,then, would very likely be to improve interference conditions within the bounds of the rules in use at the particular time, strengthening the rules one step at a time.

On this basis, spectrum manager might decide next to improve his understanding of the effects of equipment characteristics on the incidence of interference. Based upon this improved understanding, he could then begin to specify minimum stsndards for those characteristics which proved most cost effective in improving the overall level of interference. Almost every aspect of the interference problem has some uncertainty and variability associated with it. Characteristics vary from one piece of equipment to another, with age and state of maintenance. Pieces of mobile equipment move from one place to another and have operational duty cycles. Radio propagation varies with

location and time. In order to predict interference with a known degree of certainty, all of these must be modeled statistically. This is an area that should be given a great deal of emphasis if answers are to be provided in truly meaningful engineering terms.

The spectrum manager, having improved the efficiency of spectrum use through better control of the environment and through improved equipment characteristics, might wish in his next step to explore new and more efficient modulation and multiplexing techniques. The homogeneous pattern of authorized modulations, powers, bandwidths, and types of service now in use has made the potential for interference easier to understand and control. However, these patterns have limited the ability of the spectrum manager to take advantage of new and more efficient techniques which do not fit into the established pattern. Computer simulation would provide the answer. Since no established user of the spectrum could be expected to gracefully accept an expensive displacement just to accommodate other or future users, answers would have to be sought which would allow the phased introduction of the new techniques without disruption of the existing services. The simulation could provide the design tool needed to explore the compatibility of alien techniques or usage pattern without the danger of disruption. Spread spectrum techniques might be able to coexist with mobile FM, but only a detailed simulation, supported by measurments, could tell the whole story and provide the basis for a well supported low risk proposal.

What is the DOD doing in the United States to balance this, to contribute, to improve the situation? All DOD frequencies are assigned by the Interdepartment Radio Advisory Communications (IRAC), which works very closely with the Federal Communication Commission (FCC)

in doing their work. In order to determine what frequencies would best serve their purposes, the Army, the Navy with the Marine Corps, and the Air Force all operate frequency management offices manned by experienced, competent people. Their work goes a long way toward making sure that the DOD needs are met in the most effective way, and that the IRAC decisions are based on the most solid engineering foundation that they can provide. The DOD is spending a lot of the taxpayers' money on research and development, and a good deal of it contributes to making available more channels, improved coding techniques, better frequency stability components, and they have not reached yet the limit of the useful spectrum. [Ref. 1]

The military has many vehicles that need to travel on the spectrum highway. DOD's use of the electromagnetic spectrum must be in consonance with that of all other users, government and civil. The highway obviously must be shared. The DOD is working on solutions that should be useful to many people.

III. SPREAD SPECTRUM SYSTEMS

A. INTRODUCTION

Spread spectrum applications started with the first communicator who set up a scheduled time to send and receive messages. This scheduling may have come about through a desire to avoid heavy traffic (consider, for instance, 10 Indian smoke signalers talking at once) or a desire to avoid interception by surprising the would-be interceptor. The same technique of timing was adapted by radio operators, but they added a new dimension, frequency. The radio operator not only could schedule his transmissions for a time unknown to an interceptor but could transmit at one of many frequencies, which forced the interceptor to ''find'' his transmission in addition to guessing his schedule. Encoding of messages for error correction and improved time and frequency selection naturally followed.

Spread spectrum developments actually began in the 1940 as the result of ''clever engineering'' on a selected basis, with most applications involving military problems. A definition of spread spectrum that adequately reflects the characteristics of this technique is as follows:

> Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information, the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery. [Ref. 8: p. 855]

Under this definition the basic signal characteristics of modern spread spectrum systems are as follows:

32

1. The transmission bandwidth is much greater than the minimum bandwidth required to transmit the information signal.

2. Demodulation must be accomplished, in part, by correlation of the received signal with a replica of the signal used in the transmitter to spread the information signal.

3. The carrier is a nearly unpredictable, or pseudo-random, wide band signal.

There are many reasons for spreading the spectrum, and if done properly, a multiplicity of benefits can accrue simultaneously. Some of these are:

- Antijamming
- Anti-interference
- Low probability of intercept
- Multiple user random access communications with selective addressing capability
- High resolution ranging
- Accurate universal timing.

The technology has only recently become popularized in the general technical community. As the advancements progressed, the spread spectrum signaling concepts have been found to be well suited to precision range and position location and most recently have been successfully applied to multiple access situations involving many users simultaneously. The advances in modern technology, making circuitry and systems reasonably small, reliable, and inexpensive, have permitted the practical implementation of spread spectrum techniques for the transmission of digital information. Compared to usual transmission systems, spread spectrum systems permit communication of information reducing the jamming effects and protecting the message from eavesdropping. These advantages are achieved at the expense of an increased bandwidth of the modulated signal. The bandwidth thus becomes a critical parameter in the receiver design of such systems.

Much of today's prime effort is being spent in the area of developing compatible, low density signaling structures that can not only improve spread spectrum system performance but provide peaceful coexistence with other systems.

B.   WHAT IS A SPREAD SPECTRUM SYSTEM?

Every transmitting or modulating system has a characteristic signature that includes not only the frequency at which the signal is centered, but also the bandwidth of the signal when modulated by the intended signaling waveform. A spectrum is the frequency-domain representation of the signal and especially the modulated signal.

A spread sprectrum system is one in which the transmitted signal is spread over a wide frequency band, much wider, in fact, than the minimum bandwidth required to transmit the information being sent. A voice signal, for example, can be sent with amplitude modulation in a bandwidth only twice that of the information itself. Other forms of modulation, such as low deviation FM or single sideband AM, also permit information to be transmitted in a bandwidth comparable to the bandwidth of the information itself. A spread spectrum system, on the other hand, often takes a baseband signal with a bandwidth of only a few kilohertz, and distributes it over a band that may be many megahertz wide. This is accomplished by modulating with the information to be send and with a wideband encoding signal.

The basis of spread spectrum technology is expressed by C.E Shannon in the form of channel capacity:

$$C = W \log_2(1 + S/N) \qquad \text{(eqn. 3.1)}$$

where C = channel capacity, bits/s
       W = transmission bandwidth, Hz
       N = noise power
       S = signal power

This equation shows the relationship between the ability of a channel to transfer error-free information, compared with the signal-to-noise ratio existing in the channel, and the bandwidth used to transmit the information.

Letting C be the desired system information rate and changing bases, we find

$$C/W = 1.44 \log(1 + S/N)$$

and for S/N small, say < 0.1 (as one would wish it to be in an antijam system),

$$C/W = 1.44 S/N$$

and

$$W = NC/1.44S$$

thus we see that for any given noise-to-signal ratio we can have a low information - error rate by increasing the bandwidth used to transfer the information.

Incidentally, the information itself may be embedded in the spread spectrum signal by several methods. The most common is that of adding the information to the spectrum-spreading code before it's used for spreading modulation. This technique is applicable to any spread spectrum system that uses a code sequence to determine it's RF bandwidth.

Of course, the information to be sent must be in some digital form because addition to a code sequence involves modulo - 2 addition to a binary code. Alternately, information may be used to modulate a carrier before spreading it. This is usually done by some form of angle modulation, for the need in spread spectrum systems in often to output a constant-power RF envelope. [Ref. 2]

Also, the normalized error-free capacity, equation 3.1, is given by:

$$C/W = \log_2(1 + S/N_oW) = \log_2[1 + E_b/N_o(C/W)] \qquad \text{(eqn. 3.2)}$$

where N_o = single-sided noise power spectral density, W/Hz

E_b = energy per bit of the received signal

If the information rate, R, at the channel input is less than C, Shannon proved that it is theoretically possible through coding to achieve error-free transmission through the channel. This result does not provide a constructive means for finding codes that will achieve error-free transmission, but it does provide a yardstick by which the performance of practical communication schemes may be measured. A graphical presentation of equation 3.2 is obtained by setting the rate R equal to C and plotting E_b/N_o as a function of R/W, as shown in Figure 3.1.

At points below and to the right of the curve, no amount of coding or complexity will achieve totally reliable transmission. At points above and to the left of the curve, zero error transmission is possible, although perhaps at a very high price in terms of bandwidth, complexity, or transmission delay. Note that data transmission is possible at all points in the plane of Figure 3.1, but some errors are unavoidable at rates above capacity.
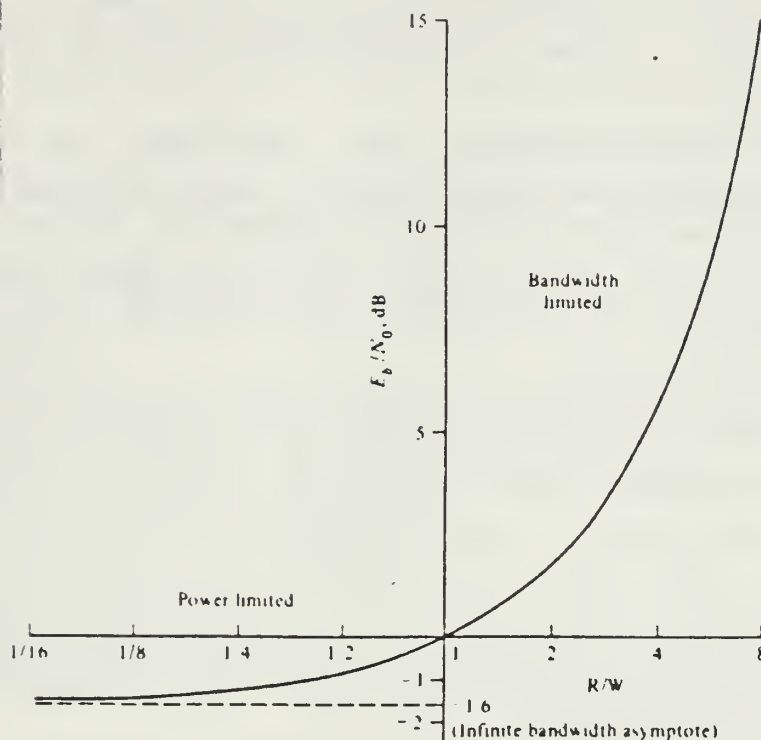
[Ref. 9: p. 8]

Figure 3.1   Power-bandwidth Trade-off for Error-free
Transmission Through Noisy, Bandlimited
Channels.

This plot can be separated into a power-limited region,
where R/W < 1, and a bandwidth-limited region, where R/W > 1.
That is, if the number of bits/s/Hz is greater than unity,
one has an efficient scheme in terms of utilizing
bandwidth. Even more important to note, however, is that
this is simply one point on the graph, for any given rate-
to-bandwidth ratio, a signal-to-noise ratio exists above
which error-free transmission is possible and below which
it is not. Quite often, practical communication schemes are
compared with this ideal by choosing some suitable
probability of error, say 10^{-6}, and finding the signal-to

37

noise ratio necessary to achieve it. This signal-to-noise ratio is then plotted versus R/W for the system, where W is found according to some suitable definition of bandwidth. [Ref. 9].

A spread spectrum system, then, must meet two criteria:
1. The transmitted bandwidth is much greater than the bandwidth or rate of the information being sent and
2. Some function other than the information being sent is employed to determine the resulting modulated RF bandwidth.

This is the essence of spread spectrum communications, the art of expanding the bandwidth of a signal, transmitting that expanded signal, and recovering the desired signal by remapping the received spread spectrum into the original information bandwidth. Furthermore, in the process of carrying out this series of bandwidth trades the purpose is to allow the system to deliver error-free information in a noisy signal environment.

C.   SPREAD SPECTRUM PRINCIPLES

The basic principles of spread spectrum modulation and communications system properties rest on the pioneering work of C. Shannon (1948) and V. Kotelnikov (1947). Shannon showed that a communications system performance is directly related to the time bandwidth-power product of the trans-mitted signal. Spread spectrum modulation is characterized by a large time-bandwidth product to achieve desirable performance. Kotelnikov showed that in a white noise inter-ference enviroment the detection demodulation performance of a transmitted symbol only depends on the received symbol energy. Thus, for a system employing a large time-bandwidth product, there is great freedom in choice of the symbol waveform without effecting the performance.

38

In a world beset by too little RF spectrum to satisfy the ever - growing demands of military, commercial, and private users the question ''why spread spectrum'' must certainly be considered valid, for spread sprectrum systems have almost as many reasons for being as they have users. Some of the properties that may be cited are the following:

1. Selective addressing capability.
2. Code division multiplexing is possible for multiple access.
3. Low-density power spectra for signal hiding.
4. Low Probability of Intercept (LPI).
5. High-resolution ranging.
6. Interference rejection.
7. Jam resistance.

These properties come about as a result of the coded signal format and the wide signal bandwidth that results. A single receiver or group of receivers may be addressed by assigning a given reference code to them, whereas others are given a different code. Selective addressing can then be as simple as transmitting the proper code sequence as modulation.

Not all of these characteristics, however, are necessarily availiable from the same system at the same time. It is somewhat anomalous, for instance, to expect, at the same time, a signal that is easily hidden but can also be received in the face of a large amount of interference. Signal-hiding requirements and interference rejection are often at odds, but the same system might be used for both by using low-power transmission when low detectability is desired and high-power transmissions when maximum interference rejection is needed.

When codes are properly chosen for low cross correlation, minimum interference occurs between users, and receivers set to use different codes are reached only by

transmitters sending that code. Thus, more than one signal can be unambiguously transmitted on the same frequency and at the same time, selective addressing and code-division multiplexing are implemented by the coded modulation format.

Because of the wideband signal spectra generated by code modulation, the power transmitted is low in any narrow region. At any rate, the density of a spread spectrum signal is far less than that of more conventional signals in which all the transmitted power is sent in a band of frequencies commensurate with the baseband information bandwidth. Again, because of the coded signals employed, an eavesdropper cannot casually listen to messages being sent. Though the systems may not be ''secure,'' some conscious effort must be made to decode the messages. Resolution in ranging is afforded in accordance with the code rates used, and the sequence length determines maximum unambiguous range. Ranging has been the most prominent and certainly the best known use of spread spectrum systems. [Ref. 2]

Several basic spread spectrum techniques are available to the communication system-designer. The tradeoffs between techniques used will determine what advantages or disadvantages will be enhanced or suppressed. Some of these techniques will be discussed in order to provide the reader with a more comprehensive view of spread spectrum capabilities.

D. SPREAD SPECTRUM SYSTEMS TECHNIQUES
    1. Direct Sequence Systems
        Direct sequence (or, to be more exact, directly carrier-modulated, code sequence modulation) systems are the best known and most widely used spread spectrum systems This is because of their relative simplicity from the

standpoint that they do not require a high-speed, fast-settling frequency synthesizer. Today, direct sequence modulation is being used for communication systems and test systems.

Direct sequence modulation is just exactly that: modulation of a carrier by a digital code sequence having a bit rate much higher than the information signal bandwidth [Ref. 10]. In the general case, the format may be AM (pulse), FM, or any other amplitude or angle modulation form. The basic form of a direct sequence signal is that produced by a simple, biphase-modulated (PSK) carrier.

Typically, the direct sequence biphase modulator has the form shown in Figure 3.2. A balanced mixer whose inputs are a code sequence and a RF carrier operates as the biphase modulator. In the time domain the biphase-modulated carrier looks like the signal shown in Figure 3.3. The simplified block diagram in Figure 3.3 illustrates a typical direct sequence communications link. It shows that the direct sequence system is similar to a conventional AM or FM communications link with code modulation overlaid on the carrier. In actual practice the carrier is not usually modulated by baseband information. The baseband information is digitized and added to the code sequence, than the carrier is modulated. After being amplified, a received signal is multiplied by a reference with the same code and, assuming that the transmitter's code and receiver's code are synchronous, the carrier invertions transmitted are removed and the original carrier restored. This narrowband restored carrier can then flow through a bandpass filter designed to pass only the baseband modulated carrier.

Undesired signals are also treated in the same process of multiplication by the receiver's reference that maps the received direct sequence signal into the original carrier bandwidth. Any incoming signal not synchronous with

41
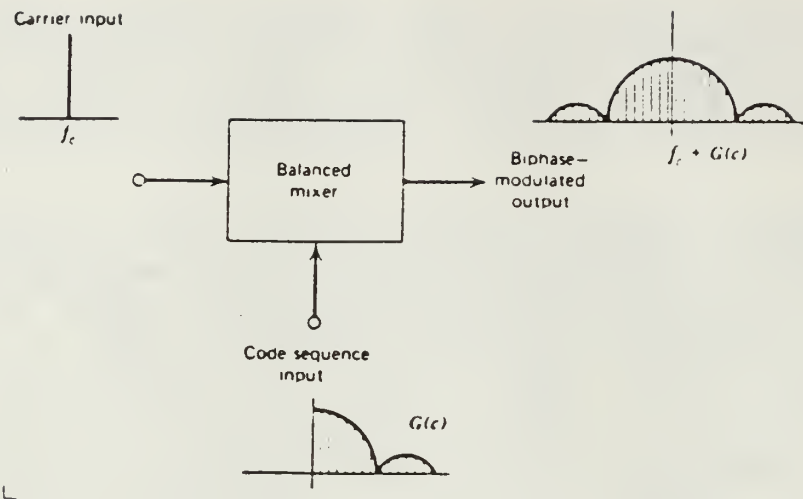
Figure 3.2   Direct Sequence Modulator (Biphase).

the receiver's coded reference is spread to a bandwidth equal to it's own bandwidth plus the bandwidth of the reference, that is, the receiver's multiplier output signal variance is the covariance of it's output signals. Because an asynchronized input signal is mapped into a bandwidth at least as wide as the receiver's reference, the bandpass filter can reject almost all the power of an undesired signal. This is the mechanism by which process gain is realized in a direct sequence system, that is, the receiver transforms synchronous input signals from the code-modulated bandwidth to the baseband-modulated bandwidth. At the same time nonsynchronous input signals are spread at least over the code-modulated bandwidth.

In any case, the direct sequence system has a main lobe bandwidth that is a function of the waveshape and the code rate used. The spectral power envelope of a direct sequence signal is of a $[(\sin x)/x]^2$ form and null-to-null
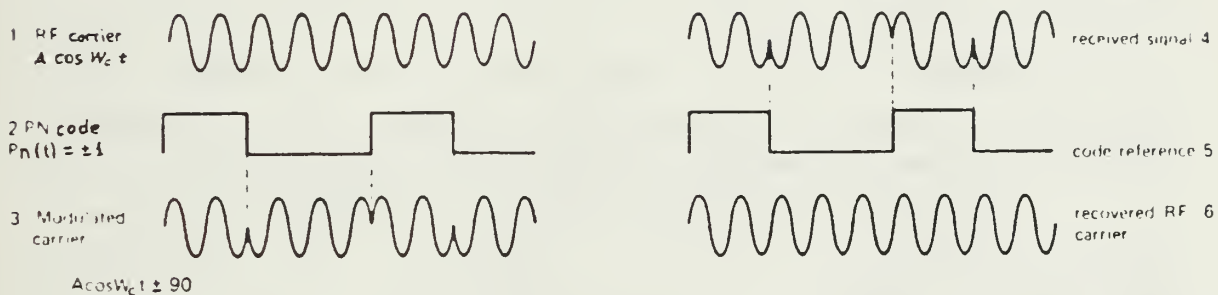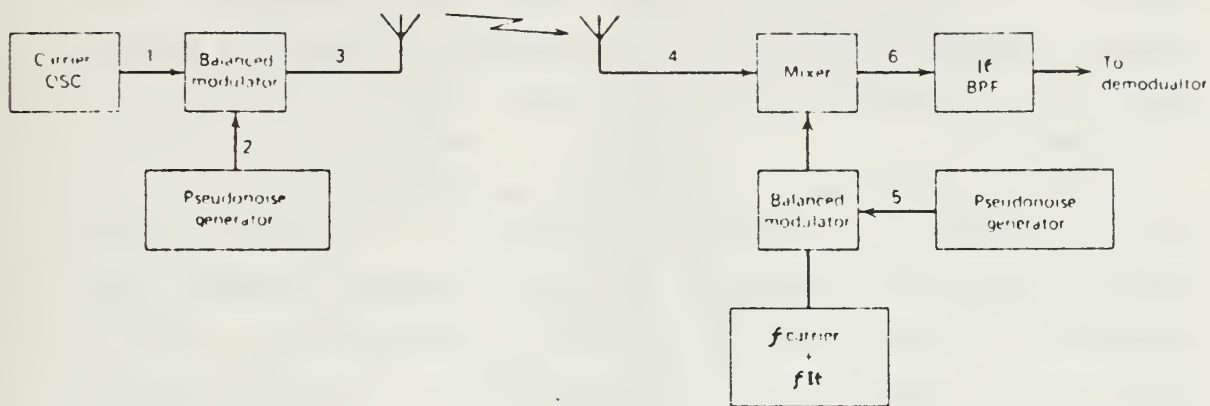
[Ref. 2: p. 18]

Figure 3.3 Overall Direct Sequence System.

bandwidth is $2R_c$. This is an expected result since any good
set of Fourier transform pairs will show that the frequency
function corresponding to a square pulse is $(\sin x)/x$
(which is a voltage distribution function) and code
modulation produces a series of pulses. Because the power
envelope is a function of the voltage squared, the
$[(\sin x)/x]^2$ power spectrum results. [Ref. 2]

   2.   Frequency Hopping Systems

        Frequency hopping modulation is more accurately
termed ''multiple-frequency, code-selected, frequency shift

keying.'' It is nothing more than FSK (Frequency Shift Keying) except that the set of frequency choices is greatly expanded. Simple FSK most often uses only two frequencies, for example f_1 is sent to signify a ''mark,'' f_2 to signify a ''space.'' Frequency ''hoppers,''on the other hand, often have thousands of frequencies available. One real system has 2^{20} discrete frequency choices, randomly chosen, each selected on the basis of a code in combination with the information transmitted. The number of frequency choices and the rate of hopping from frequency to frequency in any frequency hopper is governed by the requirements placed on it for a particular use.

Figure 3.4 is a simplified block diagram of a frequency hopping transmission system. The frequency spectrum of this frequency hopper is shown in Figure 3.5.

A frequency hopping system or ''frequency hopper'' consists basically of a code generator and a frequency synthesizer capable of responding to the coded output of the code generator. A great deal of effort has been expended in developing rapid-response frequency synthesizers for spread spectrum systems. Ideally, the instantaneous frequency hopper output is a single frequency. Practically, however, the system user must be satisfied with an output spectrum which is a composite of the desired frequencies, sidebands generated by hopping, and spurious frequencies generated as by-products. Over a period of time, the ideal frequency hopping spectrum would be perfectly rectangular, with transmissions distributed evenly in every available frequency channel. The transmitter should also be designed to transmit, to a degree as close as practical, the same amount of power in every channel. The received frequency hopping signal is mixed with a locally generated replica, which is offset a fixed amount which produces a constant difference frequency f_{IF} when transmitter and receiver code sequences are in synchronism.
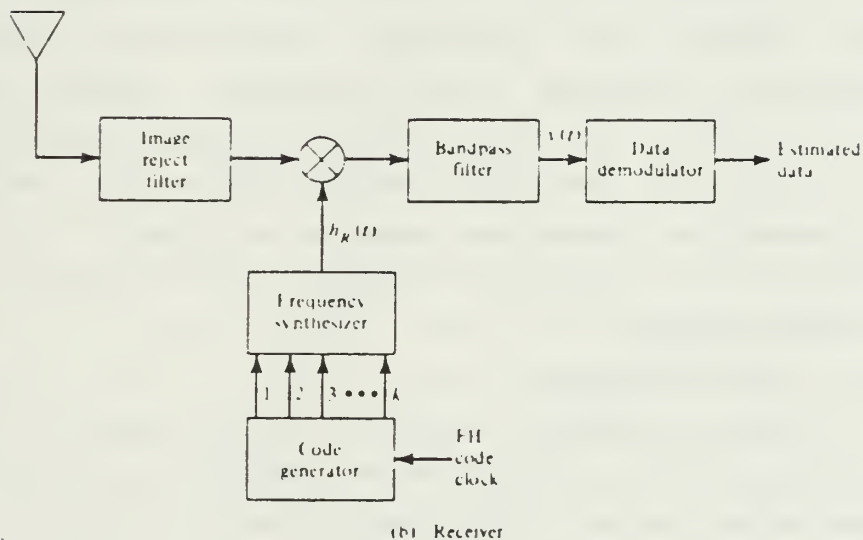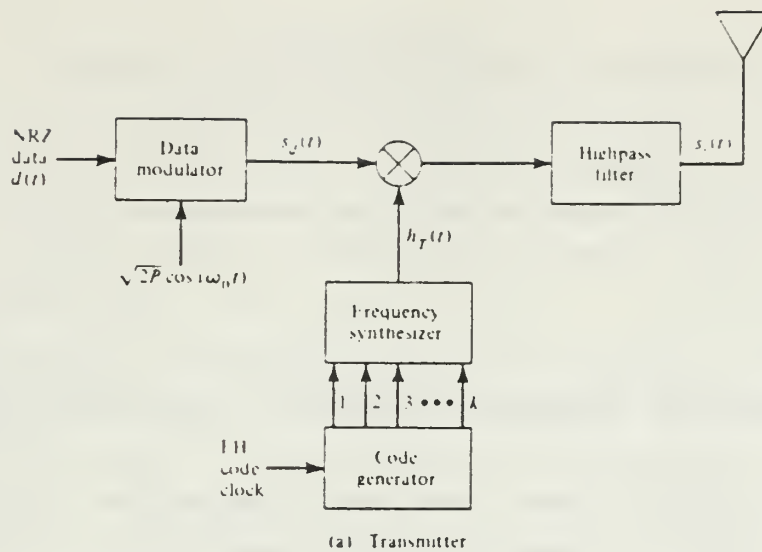
[Ref. 9: p. 349]

Figure 3.4 Basic Frequency Hopping System.

As in a direct sequence system, any signal that is not a replica of the local reference is spread by multiplication with the local reference. Bandwidth of an undesired signal after multiplication with the local reference is again equal to the covariance of the two

45
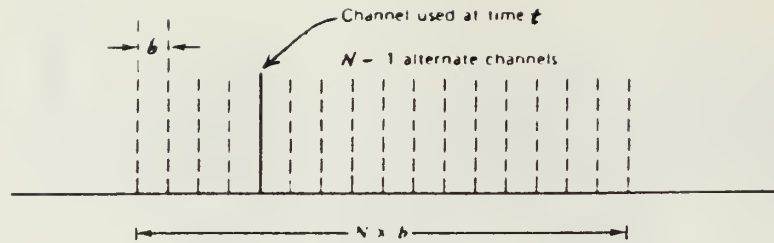
Figure 3.5   Frequency Hopping Signal Spectrum.

signals. A signal with the same bandwidth as the local
reference   (but   nonsynchronous)   would   have   twice   the
reference bandwidth at the IF. The IF following the
correlator, then, can reject all of the undesired signal
power that lies outside its bandwidth. Because this IF
bandwidth is only a fraction of the bandwidth of the local
reference, we can see . that almost all the undesired
signal's power is rejected, whereas a desired signal is
enhanced by being correlated with the local reference.

    3. <u>Other Systems</u>

        a. Time Hopping

        Time hopping, in other words, is the familiar
pulse modulation, that is, the code sequence is used to key
the transmitter on and off. Transmitter on and off times
are therefore pseudorandom, like the code, which can give
an average transmit duty cycle of as much as 50%. The main
point of difference separating time frequency and plain
frequency hopping is that in frequency hopping systems the
transmitted frequency is changed at each code chip time,
whereas a time – hopping frequency system may change
frequency only at one/zero transitions in the code
sequence. Time hopping may be used to aid in reducing
interference between systems in time-division multiplexing.

46

Simple time-hopping modulation offers little in the way of interference rejection because a continuous carrier at the signal center frequency can block communications effectively. The primary advantage offered is the reduced duty cycle. The power required of the reduced-duty-cycle time hopper would be less than that of the interfering transmitter by a factor equal to the signal duty cycle. Because of this relative vulnerability to interference simple time-hopping transmissions should not be used for antijamming unless combind with frequency hopping to prevent single frequency interferers from causing significant losses. For ranging, multiple access, or other special uses time hopping may be especially useful, if only because of the simplicity of generating the transmitted signal. [Ref. 2]

  b. Pulsed FM (Chirp) Systems

    One type of spread spectrum modulation that does not necessarily employ coding but does use a wider bandwidth than the minimum required so that it can realize processing gain is ''chirp''modulation. This form has found its main application in radar but is also applicable to communications. Chirp transmissions are characterized by pulsed RF signals whose frequency varies in some known way during each pulse period. The advantage of these transmissions for radar is that significant power reduction is possible.

  c. Hybrid Forms

    In addition to the more usual forms of spread spectrum modulation, there are hybrid combinations of modulation. One reason for using hybrid techniques is that some of the advantages of systems are combined in a single system, or at least extend the usefulness of the direct sequence and frequency hopping techniques. Hybrid techniques are widely used in military spread spectrum systems and

47

are currently the only practical way of achieving affective
spectrum spreading. The most often used combination (or
hybrid) spread spectrum signals are made up of:
- Simultaneous frequency hopping and direct sequence
  modulations.
- Simultaneous time and frequency hopping, and
- Simultaneous time-hopping and direct sequence
  modulations.
  (1)Frequency Hopped/Direct Sequence Modulation.
As suggested by its title, frequency hopped/direct sequence
(FH/DS) modulation consists of a direct sequence modulated
signal whose center frequency hops periodically. Figure 3.6
illustrates the frequency spectrum from such a modulator.
The spread spectrum signal shown is made up of a number of
spread spectrum signals. A direct sequence signal covering
a part of the band appears instantaneously, and the entire
signal appears in other parts of the band as dictated by a
frequency hopping pattern.
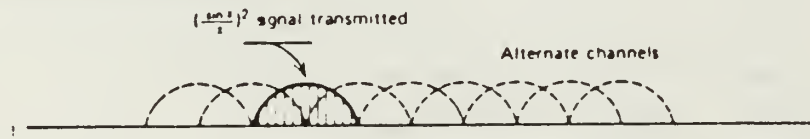
Figure 3.6 Frequency Spectrum of Hybrid FH/DS System.

Hybrid FH/DS transmitters are straight-
forward super positions of direct sequence modulation on a
frequency hopping carrier, as shown in figure 3.7. This
modulator differs from a simple direct sequence modulator
mainly in that the carrier frequency is varying (hopped)
rather than being at a constant frequency, as for simple DS
modulation. Note also that the same code sequence generator
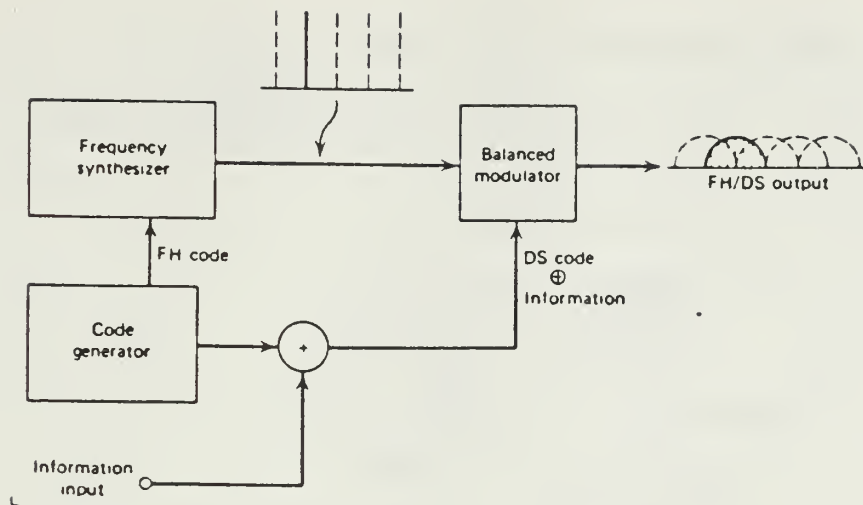
Figure 3.7 Hybrid FH/DS Modulator.

can supply code data both to the frequency synthesizer to program its hopping pattern and to the balanced modulator for direct modulation.

The correlator used to strip off the spread spectrum modulation in a receiver, before baseband demodulation, is, for FH/DS hybrids, again a super position of a direct sequence correlator on a frequency hopping correlator, that is, the local reference signal becomes a hybrid FH/DS signal, which is then multiplied with all received input signals. Figure 3.8 shows a typical FH/DS receiver configuration in which the local reference generator is essentially a replica of the transmitting modulator, with two exceptions:

- The local reference center frequency is offset an amount equal to the IF, and
- The DS code is unmodified by baseband input.

(2) <u>Time-Frequency Hopping</u>. Time frequency hopping modulation has found its greatest application in those systems in which a large number of users with widely variable distances or transmitted power are to operate

49
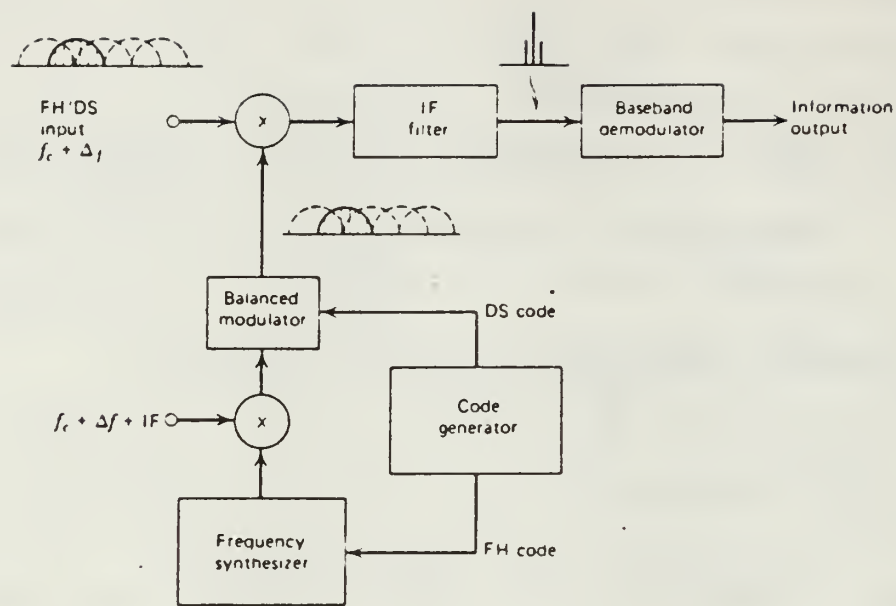
Figure 3.8 Hybrid FH/DS Receiver.

simultaneously in a single link. Such systems tend to employ simple coding, primarily as an addressing medium, rather than to spread the spectrum specifically. The general tendency is to design to the equivalent of a wireless telephone switching system in which random access and discrete address are the prime operational goals. For such uses time-frequency hopping is well adapted, it offers one of the few (and perhaps only) viable solutions to the near far problem. A good solution is to time all transmissions so that the desired and undesired transmitters are never transmitting at the same time. Even better, with time frequency hopping, two transmitters can be programmed to transmit on different frequencies as well as at different times. Many links can then be operated at once if their time slots and frequency hopping channels are properly synchronized.

(3) <u>Time-Hopping Direct Sequence</u>. When direct sequence transmission is used and code division multiplexing does not permit sufficient access to the link, time-hopping has proved to be a useful way of adding time-division multiplexing (TDM) to aid in traffic control. The high degree of time synchronization between direct sequence transmit - receive terminals because of their code correlation requirements leads ideally to time-hopping, that is, because a direct sequence receiver must align its local reference code within a fraction of a pn code chip time, it already has timing good enough to support TDM operation. All that is required to add time-hopping TDM to a direct sequence system is on-off switching and control. For time-hopping the on and off decision can easily derived from the same code sequence generator used to derive the spectrum spreading code.

E. APPLICATIONS AND ADVANTAGES

Although the current applications for spread spectrum continue to be primarily for military communications, there is a growing interest in the use of this technique for mobile radio networks (radio telephony, packet radio, amateur radio), timing and positioning systems, some specialized applications in satellites, etc. While the use of spread spectrum naturally means that each transmission utilizes a large amount of spectrum, this may be compensated for by the interference reduction capability inherent in the use of spread spectrum techniques, so that a considerable number of users might share the same spectral band. There are no easy answers to the question of whether spread spectrum is better or worse than conventional methods for such multiuser channels. However, the one issue that is clear is that spread spectrum affords an opportunity to give a

51

desired signal a power advantage over many types of interference, including most intentional interference (i.e., jamming). Three of the most important benefits are:

1. Interference Suppression
2. Energy Density Reduction
3. Ranging or Time Delay Measurment.

The most important among these is the suppression of interference which may be characterized as any combination of the following: [Ref. 11]

(1) Other users: intentional or unintentional.
(2) Multiple access: spectrum sharing by coordinated users, and
(3) Multipath: self-jamming by delayed signal.

Protection against in-band interference is usually called anti-jamming. Probably the single most important application in spread spectrum techniques is the resistance to intentional interference or jamming. Both direct-sequence (DS) and frequency-hopping (FH) systems exhibit this tolerance to jamming, although one might perform better than the other given a specific type of jammer.

A similar application is that the multiple access by numerous users who share the same spectrum. As is well known, the two most common multiple access techniques are Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). In FDMA, all users transmit simultaneously, but use disjoint frequency bands. In TDMA all users occupy the same RF bandwidth, but transmit sequentially in time. When users are allowed to transmit simultaneously in time and occupy the same RF bandwidth as well some other means of separating the signals at the receiver must be available, and Spread Spectrum Multiple Access (SSMA) [also termed Code Division Multiple Access (CDMA)] provides this necessary capability.

52

The advantages of SSMA are: [Ref. 12]

- It does not need any timing coordination.
- It has simultaneous random access.
- More importantly, repeater bandwidth of a satellite is utilized efficiently and no guard bands are inserted.
- It provides simultaneous ranging with telephone communication.

Although TDMA satellite communication provides the highest traffic capacity per satellite and offers efficient transmission of a wide variety of services, it suffers from network timing and ranging requirements and message security. On the other hand, SSMA satellite communication is suited for reliable random access and tactical transmission systems. So, the hybrid system, a combination of TDMA and SSMA can be used for asynchronous and reliable transmission of digital and analog signals. The hybrid system, also, may use frequency hopping spread spectrum to insure anti-jamming capability of the TDMA system.

The third form of interference suppressed by spread spectrum techniques is the self interference caused by multipath in which delayed versions of the signal, arriving via alternate paths, interfere with the direct path transmission. That is true, because as long as the signal is hopping fast enough relative to the differential time delay between the desired signal and the multipath signal (or signals), all (or most) of the multipath energy will fall in slots that are orthogonal to the slot that the desired signal currently occupies.

Finally, the three problems of interference are often all present in a given system, and so the use of an appropriate spectrum-spreading technique can alleviate all three problems at once. If only multiple access capability is needed, there are systems other than SSMA that can be used. However, when multipath is also a problem, the choice of SSMA as the multiple accessing technique is

especially appropriate since the same signal design allows both many simultaneous users and improved performance of each user individually relative to the multipath channel. In the case of signals transmitted over channels degraded by both multipath and intentional interference, spread spectrum is a virtual necessity.

The second class of applications centers about the reduction of the energy density of the transmitted signal. It has a three-fold purpose:

(1)   To meet international allocations regulations.

(2)   To minimize detectability, and

(3)   For privacy.

The important point in this discussion is that the same level of average radiated power is required whether this power is spread over a very wide bandwidth or is concentrated in a very narrow bandwidth. Thus, the power density radiated is less than a conventional narrowband system. Even more promising is the potential for achieving privacy in communication by spreading one's signal sufficiently to hide in the background noise.

The application of spread spectrum for ranging or position location is rapidly gaining importance. Any RF signal is subject to a fixed rate of propagation (approximately 6 μsec/mi). The signal reaching a receiver at any given instant left the transmitter that sent it some time before. Because signaling waveforms or modulations are also functions of time, the difference in a signaling waveform, a seen at a receiver, from that present at the transmiter can be related directly to distance between them and used to measure that distance. Any signal used is subject to the same distance/time relations. The spread spectrum signal has an advantage, however, in that its phase is easily resolvable. The advantage of spread spectrum ranging is that the timing measurment is made using the

spreading code as the standard of measure. Highly accurate ranging measurments can be obtained when high code bit rates are used. The highest-resolution spread spectrum systems known can measure range to approximately 1/1000th of a chip period.

Some areas in which spread spectrum methods (or at least system components) have already been put to good use are given in Table II.

TABLE II

SPREAD SPECTRUM SYSTEMS APPLICATIONS

Area	Application	Type of System	Primary User
Space Systems	Communications, ranging, multiple accessing, jamming protection.	Direct sequence. Frequency hopping.	Military
Avionics Systems	Communications, position location, discrete addressing, low detectability, jamming protection, radar, collision avoidance.	D.S. F.H. Hybrid DS/FH. Chirp.	Military
Test systems and equipment	Bit-error detection, noninterfering in-service testing, signal correlation, privacy, (pseudo-) random selection, number generation.	Direct sequence	Commercial

| Signal protection (nonmilitary) | Interference rejection, voice and data scrambling. | Direct sequence | Commercial |
| Position location | Collision avoidance, direction finding, ranging. | Direct sequence | Many |

In space systems, especially communications satellites, which may be stationary and therefore continuously accessible to interference, spread spectrum methods have proved effective. One space-oriented system that makes use of spread spectrum modulation to advantage is the Tracking and Data Relay Satellite System (TDRSS). This system is one of the few that make use of spread spectrum modulation for some reason other than antijamming. The reason for its use in TDRSS is to reduce the power density of the signals as seen at the earth's surface. Signal level from space are limited to a density of 145 dBm in a 4 KHz bandwidth, in a square meter aperture, and TDRSS accomplishes this by transmitting a 3.08 Mcps direct sequence modulated signal. The TDRSS system will provide relay of signals from orbiting spacecraft, where 100% coverage is provided by only two TDRSS spacecraft for all users whose orbits are at least 1200 Km above the earth's surface.

Another satellite-type spread spectrum system is the Global Positioning System (GPS), which is a ranging system used by mobile users to determine accurately their position on the earth's surface. The military name for GPS is NAVSTAR. This system will make use of a constellation of 18 satellites, each in a 12 hour circular orbit 12,211 miles above the earth, with up to six satellites in view at any time over a large portion of the earth's surface. The idea behind GPS is to transmit spread spectrum signals that

allow a range measurement, from a known satellite location (the transmitter on board the satellite tells the receiver the satellite location). Then, with a knowledge of the transmitter location and the distance to the satellite, the receiver can locate itself on a sphere whose radius is the distance measured. After receiving signals and making range measurements on other satellites, the receiver can calculate its position based on the intersection of several spheres.

Avionics systems can employ spread spectrum methods in any of the ways available to satellites and other systems. Ranging, direction finding, discrete addressing, and communicating are all within the realm of practicality. The oldest of the avionics systems is the ARC-50. This is a direct-sequence modem for voice communications, but is also capable of ranging, and reads out range to 1/10 mile at ranges of up to 300 miles.

A frequency hopping UHF AM radio adapted from the ARC-164 radio. Have Quick will be the first widely used spread spectrum radio. The Have Quick configuration will be a standard for at least the next 10 years. [Ref. 2]

The Joint Tactical Information Distribution System (JTIDS) is a tactical military spread - spectrum radio network which is currently being developed in the United States. This system will provide jam-resistant communications and location for troops in combat situations and is being developed with support from all the military services and NATO. Jamming resistance is achieved using a hybrid direct - sequence / frequency - hop / time-hop transmission strategy.

IV. SPREAD SPECTRUM SYSTEMS PERFORMANCE ANALYSIS

A. INTRODUCTION

A fundamental question for spread spectrum performance analysis is what performance criterion should be used. There are a large number of criteria that might be used to measure the goodness of a communication system to see if it is ''ideal'' or ''perfect''. Some of these are cost, channel bandwidth used, required transmitter power, signal-to-noise ratios at various points of the system, probability of bit error for digital systems, and time delay through the system.

Although the detection signal-to-noise ratio for analog communication and the bit error probability for digital communication are natural performance measures, they do not by themselves completely define the criterion since the properties of the interference signal are not necessarily explicit. Generally, spread spectrum modulation is used in an unknown interference environment that either lacks a statistical or deterministic characterizations or makes such an assumption artificial and most disconcerting from a system design point of view. Any particular assumption will always leave the uneasy feeling that the most critical case may not have been considered. Therefore, the object of spread spectrum performance analysis is to ensure a minimum system performance under all conditions.

Optimization of the performance of a communication system operating over a general channel in the presence of unknown interference requires determining the worst case interference of each communication system. Thus, to maximize communication system performance in terms of

probability of error or average interference power requires that: [Ref. 13]

1. The performance of each modulation/coding technique available to the communicator be determined for each possible interference.

2. The worst case interference, which minimizes the communication system performance, be established for each modulation coding technique, and

3. The communicator select the modulation / coding technique which provides the maximum performance against the worst case interference.

In this way, the best possible communication system performance is achieved for unknown interference.

B. PERFORMANCE CRITERIA (STANDARDS) FOR SPREAD SPECTRUM COMMUNICATIONS

In spread spectrum systems either the RF bandwidth and/ or the total time epoch of the signal is ''spread'' beyond that required for basic signaling to provide special functions or to cope with unintended parties. Special functions, which may be of interest to civilian as well as military users, are ranging, multiple-access, selective addressing, antimultipath, and minimum power - density signaling. Military communications, the chief developer of spread spectrum techniques, build antijam (AJ) systems if the unintended party is a jammer and anti-intercept (AI) systems if avoidance of signal intercept is important. Spread spectrum applications are sensible divided into the cases where:

1. The links are relatively ''isolated'', and

2. The links are relatively ''dense'' and interacting. The isolation may stem either from physical separation of platform (remote ship or airplane) or from antenna-beaming (satellite uplinks). Traditional dense applications occur in omnidirectional communication links among tactical

59

mobile vehicles or aircraft. In dense applications, where many radios are within range of each other, frequency management and self interference (near-far) must be handled, as well as unintended parties. In isolated applications, usually a single radio link must cope only with the unfriendly jamming or with the possible signal exploitation interception.

When adopting spread spectrum techniques in isolated cases, the major contest is between platforms, and the ''processing gain'' of the system versus that of the unintended party. In dense cases, however, spread spectrum techniques offer yet another dimension - the denial of obvious frequency channelization to the unintended party. Traditionally this channelization provides the underlying basis for intercept-jam strategies. Potential jammers are able to monitor the spectrum activity in dense environments and relate specific spectrum activity to particullar types of vehicles or organizations for selective jamming. Adoption of spread spectrum in a frequency region should significantly after the ability of unintended parties to make sense out of the spectrum activity.

The pseudonoise (PN) sequences that are used for the spreading in any system must meet the two critical criteria of: [Ref. 14]

1. Denying any information about the future sequence K-tuples to the unintended party, and

2. Permitting practical implementation, including convenient code changes.

Sometimes it is desirable for the sequence autocorrelation behavior to have a high peak-to-side-lobe ratio, for acquisition and synchronization purposes. Finally, K-tuple statistics are desirable, depending on the type of system. Denying future information is probably the foremost criteria, if future sequence values are not totally

uncertain, the unintended party should be able to reduce the intended system processing gain, at least in AJ systems. This means that the PN code period must ecxeed the time between code changes, and the code must not be ''crackable'' in the encryption sense. If frequency hopping with FSK modulation is the AJ technique, then the first system concern is to assure sufficiently rapid hopping so as to deny any possibility of follower-jamming for the geometry-determined path delays. If a system uses Direct sequence PN for AJ, then it should anticipate a (single) tone jammer, placed near or at the PN carrier frequency.

C. PERFORMANCE OF SPREAD SPECTRUM IN A JAMMING ENVIRONMENT

1. Spread Spectrum Communication System Model

The purpose of most spread spectrum systems is to transfer information from one place to another. One figure of merit for these systems is the probability of correctly communicating a message in a particular noise and/or jamming enviroment.

Spread spectrum modulation may be implemented in many ways but always with the transmission bandwidth significantly exceeding that of the information signal.This band spreading is most commonly achived by multiplying (mixing) the information signal m(t) with a spreading waveform s(t) and amplified version of the signal

$$Re[m(t)s(t)exp(iw_0 t)]$$

centered about the carrier frequency $f_0 = w_0/2\Pi$. In Figure 4.1 the spread spectrum communications system model is shown as a block diagram including the mathematical descriptions of the signal at various points. To present the basic spread spectrum concepts most clearly, the
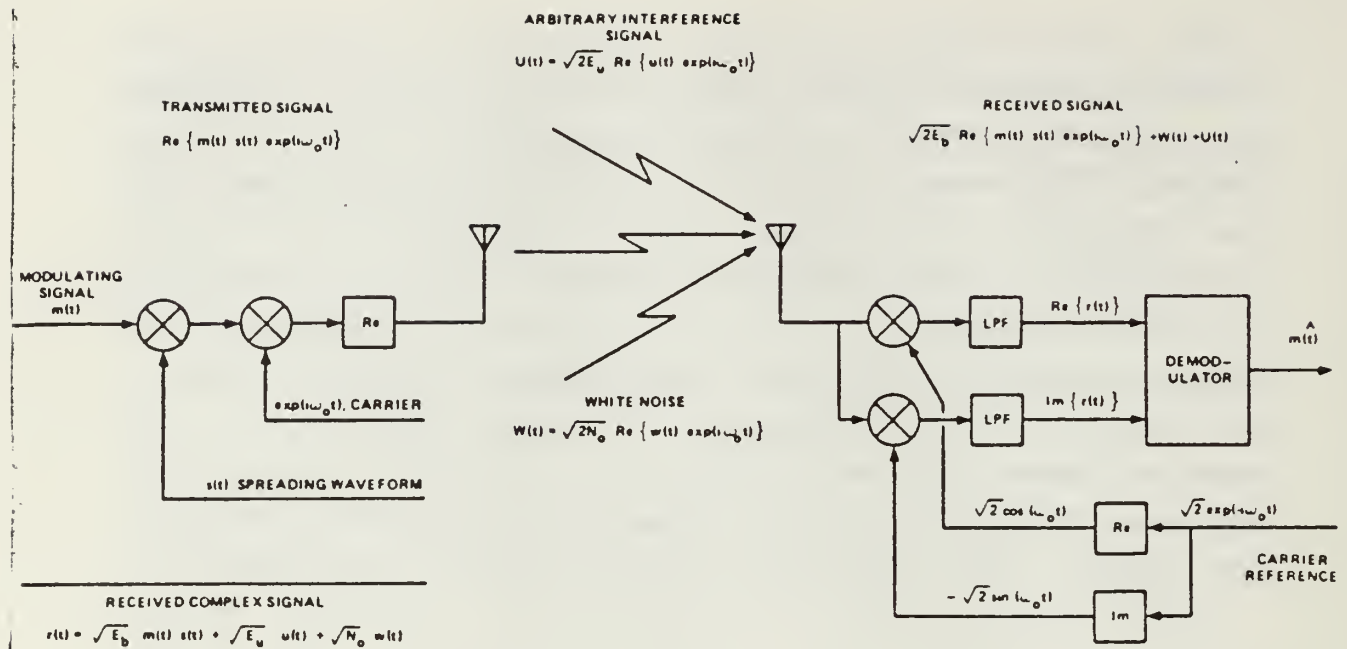
[Ref. 15: p. 849]

Figure 4.1 Spread Spectrum Communication Model.

performance investigation will be limited to binary antipodal signaling, that is, $m(t) = \pm 1$ for $t \in (0,T)$ and $m(t) = 0$ otherwise, with T being the transmitted symbol duration. The spreading waveform, $s(t)$ may be either a continuous or discrete (hopping) form of phase, frequency, or time modulation. From an analysis point of view, it is convenient to normalize the spreading waveform to have unit symbol energy, that is, $\int |s(t)|^2 dt = 1$ with integration over the symbol period, $(0,T)$. In the common case the spreading waveform has constant power, this normalization implies $|s(t)| = \sqrt{1/T}$.

Assuming that the transmitted signal is sent over a linear, nondispersive medium, the received desired signal will be

$$\sqrt{2E_b}\,\mathrm{Re}[m(t)s(t)\exp(iw_0 t)]$$

62

where E_b equals the receive bit energy over the symbol period $(0,\dot{T})$. In addition to the received desired signal, two interference signals will be considered, namely,

$$W(t) = \sqrt{2N_0}\, Re[w(t)\exp(iw_0 t)]$$

$$U(t) = \sqrt{2E_u}\, Re[u(t)\exp(iw_0 t)]$$

where $w(t)$ represents a complex, white noise (Gaussian) process of unit (double-sided) spectral density. With this definition $W(t)$ becomes a white noise process of spectral density N_0 (single-sided). The signal $u(t)$ represents a square integrable signal of the unit energy over the symbol period $(0,T)$. In this way $U(t)$ will have the energy E_u over the symbol period. As the first signal processing step, the composite received signal

$$R(t) = \sqrt{2E_b}\, Re[m(t)s(t)\exp(iw_0 t)]+W(t)+U(t) \qquad \text{(Eqn. 4.1)}$$

is multiplied (mixed) with the coherent reference $\sqrt{2}\exp(-iw_0 t) = \sqrt{2}\cos(w_0 t) - i\sqrt{2}\sin(w_0 t)$ at the receiver followed by low pass fiftering to remove the double carrier frequency compononts, thus obtaining the complex received signal

$$r(t) = [R(t)\sqrt{2}\exp(-iw_0 t)]_{LP} = \sqrt{E_b}\,m(t)s(t)+\sqrt{N_0}\,w(t)+\sqrt{E_u}\,u(t)$$

The complex nature of the receive signal $r(t)$ results from defining the signal of equation 4.1 in complex terms. The

63

transmitted signal, as well as the received signal R(t), are real signals, although their mathematical formulation incorporates complex functions just for our convenience. The real part of R(t) will be referred to as the in phase and the imaginary part as the quadrature component. [Ref. 15]

2. Signal-to-Noise Performance

The performance analysis will be possible by considering the spreading waveform random. Since the spreading waveform can be designed with known statistical properties, the performance analysis will be well defined. However this view point leads to a conceptual problem: how is it possible to generate two identical random waveforms, one at the transmitter, s(t), and one at the receiver, g(t), for the correlation processing. Now if they were truly random, it would be impossible, but one way is to use deterministic pseudorandom number or sequence generators to produce essentially random waveforms to justify this approach.

In statistical terms the spreading waveform will be defined to have zero mean and continuous covariance $K_s(t,t') = E[s(t)s^*(t')]$. With $g(t) = s(t)$ and for the period $(0,T)$ we obtain $\mu = m\sqrt{E_b}$ real-valued and therefore considered the corresponding signal – to – noise ratio $\mu^2/\text{Var}[\text{Re } n]$. The variance of $[\text{Re } n]$ is most conveniently obtained from the identity $\text{Var }[\text{Re } n] = 1/2[E|n|^2 + \text{Re}En^2]$ valid for a zero mean, complex, random variable. Yet, we can make an important observation. Whatever the ''covariance'' function $K_s(t,t')$ may be, the contribution of $\text{Re } En^2$ to $\text{Var }(\text{Re } n)$ may either be positive or negative depending on the interference signal* u(t). Therefore, it is advantageous to design a system with a spreading waveform for which $K_s(t,t')$ identically vanishes. Since we must have

64

$K_s(t,t') = E\ s(t)^2 = 0$ for some $t \in (0,T)$, it is necessary to consider $s(t)$ complex. We will term such a waveform proper if $K_s(t,t') = 0$ for all $t,t' \in (0,T)$. Such spreading waveforms do exist in abundance, since $s(t) = x(t) + iy(t)$ will be proper if $x(t)$ and $y(t)$ are uncorrelated, zero mean, real signal process with the same statistical description. So for a proper complex spreading waveform $Var[Re\ n] = 1/2[E|n|^2] = 1/2[N_0 + E_u M_s(0,T)$ where $M_s(0,T)$ is the maximum characteristic value over $(0,T)$ of the spreading waveform covariance kernel $K_s(t,t')$. Kullstam in Ref. 15 says that the results can be combined to stabilize the ensured detection signal-to-noise ratio:

$$SNR = 1/2[min(\mu^2/Var(Re\ n))] = E_b/[N_0 + E_u a M_s(0,T)] \quad [Eqn. 4.2]$$

where $a = 1$ for a proper complex and $a = 2$ for a real spreading waveform.

In obtaining SNR of equation 4.2 we considered the maximum of $a M_s(0,T)$. The minimum of $[a M_s(0,T)]^{-1}$ is referred to as the spread spectrum processing gain. For discrete phase shift modulation (phase hopping), at a rate D^{-1} it equals T/D for a proper M-ary PSK with $M \geqslant 3$, and $T/2D$ for a real binary PSK spreading waveform. This 3 dB advantage makes sense from a physical point of view since a proper spreading waveform will distribute the interference energy E_u equally in the two quadrature channels, real and imaginary, while all the desired signal energy E_b is collected into one of them.

3. <u>Bit Error Rate Performance</u>

The signal-to-noise ratio result of equation 4.2 that we obtained for binary antipodal signaling suggests that bit error probability performance $P_p = 1/2\ erf\sqrt{SNR}$. However, there is no assurance that the detection output is a Gaussian random variable when considering arbitrary

65

interference. Gaussian interference is not excluded so one can claim, considering the max-min performance objective, the lower bound .   .

$$P_p \geqslant 1/2 \, erf \; E_b/(N_0 + aE_u D/T) \qquad\qquad \text{[Eqn. 4.3]}$$

The main purpose of our analysis is to determine an upper bound of max-min P_b. For this task it is necessary to consider the detailed structure of the pseudo - random spreading waveform. The Chebyshev inequality in statistics would provide us with such a bound, but it is poor, and so in Ref. 15, the Chernoff bound is derived and applied to four-phase shift keyed (QPSK) spreading waveform modulation with independent equally probable phase hops to obtain a proper waveform. The bit error probability bound

$$P_b \leqslant exp[-E_b/(N_0 + E_u D/T)] \qquad\qquad \text{[Eqn. 4.4]}$$

is obtained where it should be noted that no restriction has been placed on the interference signal $\sqrt{E_u}\,u(t)$ except that it is limited to the energy E_u (or less) over symbol period $(0,T)$. It is not difficult to perceive that, in general, for PSK spreading waveforms, the bound max-min $P_b \leqslant exp(-SNR)$ applies with SNR given by equation 4.2. This upper bound is quite close to the lower bound of equation 4.3 for a = 1. Actually, see Figure 4.2, the difference is less than 2 dB for bit error rates less than 1×10^{-3}. With the upper bound, equation 4.4, applicable for the most general interference situation, it still seems that one should be able to improve on the Chernoff bound in view of the central limit theorem if some additional constraints of the interference are imposed. A lower upper bound can be obtained if uniform interference intensity over a certain
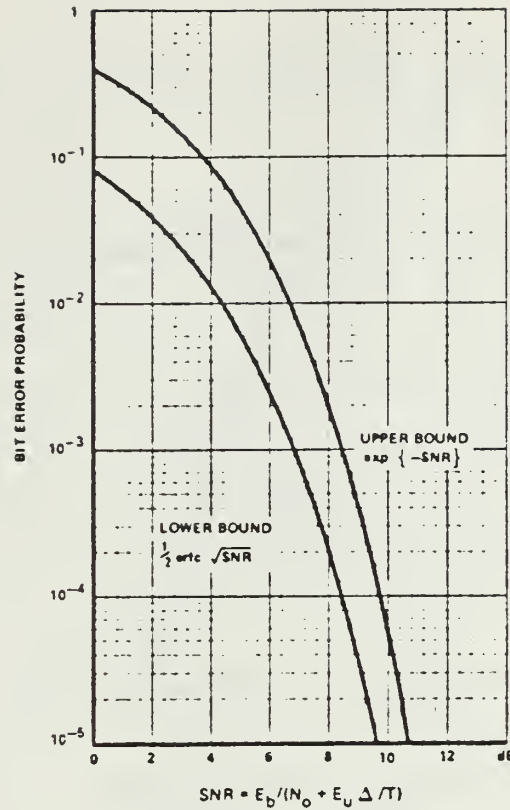
Figure 4.2   Bit Error Probability Bounds in Arbitrary Inte-
rference Using QPSK Spreading Waveform
Modulation.

portion of the symbol period can be justified.   Defined in
Ref. 15, the bit error probability bound

$$P_b < 1/2 \sqrt{(n-1)/(n-3)} \, \text{erf} \sqrt{E_b / [N_0 + E_u (D/T) n / (n-3)]} \qquad \text{[Eqn. 4.5]}$$

follows   provided $n < N = 2T/D$ and $n>3$.   This upper bound
becomes   inseparable from   equation 4.4 for   large n-values
making an analysis based on Gaussian statistics   virtually
correct. However, this result was achieved by the addition-
al constraint of uniform interference over the n/N-portion
of   the   transmitted symbol   and   thus   lacks   the general
applicability of equation 4.4.   In Figure 4.3 the closeness

67

UPPER BOUND

$$\frac{1}{2} \sqrt{\frac{n-1}{n-3}} \; \text{erfc} \; \sqrt{\text{SNR} \, (1-1/n)}$$

n = 32

LOWER BOUND

$$\frac{1}{2} \; \text{erfc} \; \sqrt{\text{SNR}}$$

BIT ERROR PROBABILITY

$$\text{SNR} = E_b/(E_U \, \Delta /T)$$
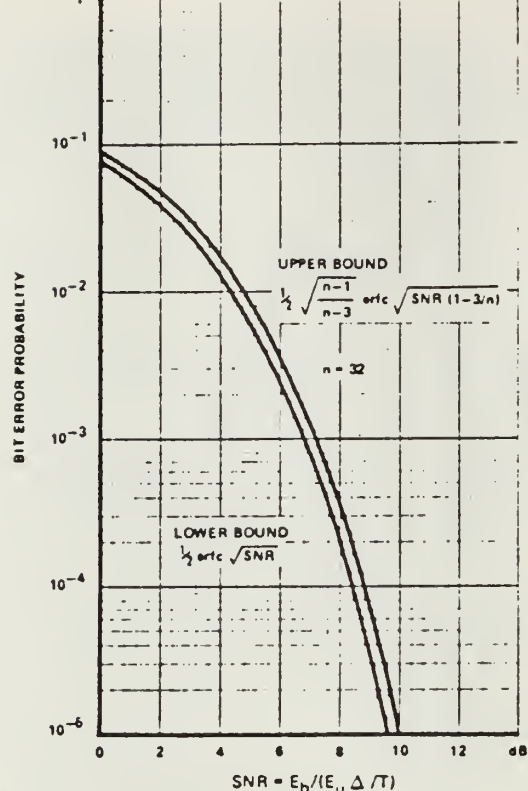
[Ref. 15: p. 852]

Figure 4.3   Bit Error Probability Bounds in Uniform Interf-
erence Using QPSK Spreading Weveform
Modulation

of equation 4.5 to the Gaussian performance graph is shown
for n=32 assuming no white noise interference.

In the derivation above the number of dimensions
N= 2T/D corresponds to the number of independent components
of the spreading waveform over the symbol period (0,T). In
other words, N represents the degree of freedom being
exercised within the symbol and generally the performance
of a spread spectrum communication system improves with N
as well as the required transmission bandwidth. If,
however, only one or a few degrees of freedom are used per
symbol out of many, as in the case of frequency hopping
spreading waveform modulation, the upper performance bound
becomes drastically different from equations 4.4 and 4.5.

68

D. PERFORMANCE OF SPREAD SPECTRUM WITH FORWARD ERROR CORRECTION

Spectrum spreading by itself produces large communication system performance improvements by effectively spreading the jammer power over the full spread communication bandwidth. The effect of worst-case jamming can be further mitigated using one or more of the powerful forward error correction (FEC) techniques which have been developed following Shannon's pioneering work. Error correction coding is an extremely complex topic. In this thesis a small number of the most basic concepts of FEC are discussed in order to give a preliminary idea of the power of these techniques.

The most effective jamming strategies are those which concentrate jamming resources on some fraction of the transmitted symbols using either pulsed or partial band techniques. A result of these jamming strategies is that demodulator output errors occur in bursts. Because the FEC techniques perform best when channel errors are independent from one signaling interval to the next, interleaving is assumed for all FEC schemes. The purpose of the interleaver is to rearrange the order in which coder output symbols are transmitted so that bursts of transmission errors will not appear as a burst at the decoder input. The system model for the coded spread spectrum system is the model illustrated in Figure 4.4. [Ref. 9].

1. Elementary Block Coding Concepts

Block codes can be either linear or nonlinear. Consider only encoders whose input and output is binary. A block encoder groups K input binary symbols into a word and outputs an n-bit binary codeword. The code rate is $R = K/n$. There are 2^K possible input words and each has a unique output codeword associated with it. Since there are 2^n possible output codewords and $K < n$, not all possible output
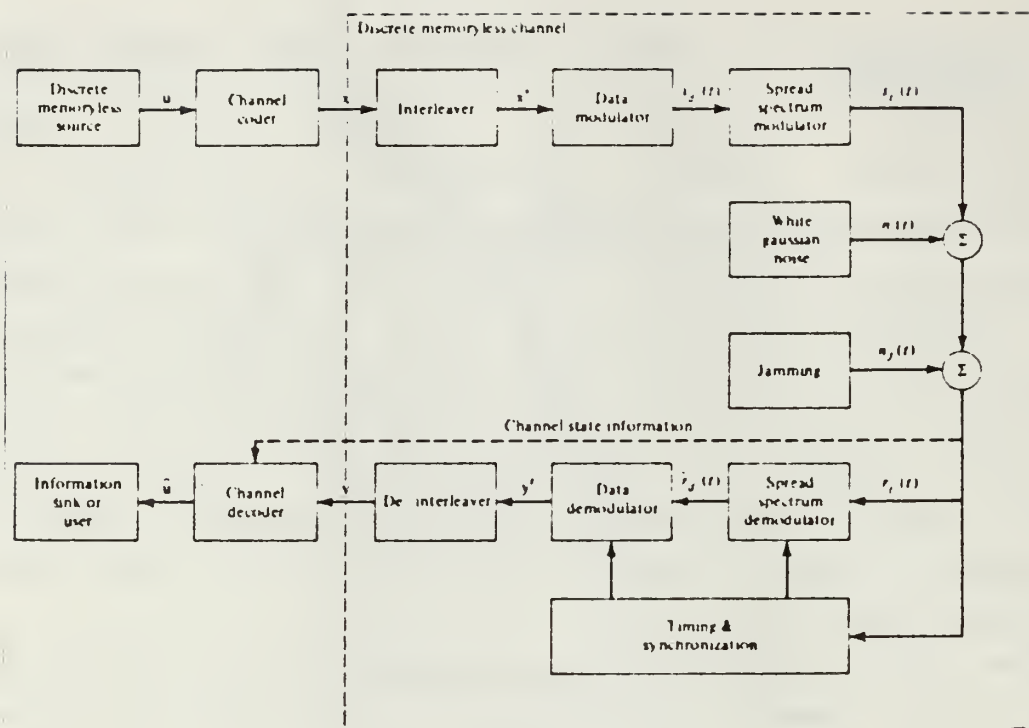
[Ref. 9: p. 556]

Figure 4.4   Spread Spectrum Communication Model.

codewords are used. The error correction capability of any
error correction code is due to the fact that not all
possible encoder output-tuples are used. Because of this,
it is possible to generate codes with codewords selected so
that a number of transmission errors must occur before one
codeword will be confused with another. Codewords are
represented by binary n-tuples $x_m = (x_{m1}, x_{m2}, . . ., x_{mn})$
where m = 0, 1, 2, . . ., 2^K-1 is the message associated
with the codeword. Any two codewords x_m and $x_{m'}$ which
differ from one another in d_H places and agree in $n-d_H$
places are said to be separated by Hamming distance d_H.
A total of d_H transmission errors must occur befor x_m is
changed into $x_{m'}$. The minimum Hamming distance between any
two of the 2^K codewords in a code is the minimum distance
d_{min} of the code. An (n,K) binary block code uses a

70

fraction $2^K/2^n = 2^{K-n}$ of all possible output codewords. A low-rate code uses a smaller fraction of the possible output words than a high rate code and codewords can therefore be separated further from one another. Thus low rate codes typically have more error correction capability than high-rate codes.

A linear binary block code may be thought of as a mapping of encoder input messages into encoder output codewords. The codewords are carefully selected to be seperated as far as possible in Hamming distance. The decoder input is a distorted version of the encoder output. The decoder operates by choosing as its estimate of the transmmited codeword the codeword which is ''closest'' to the receive n-tuple y. The distance measure used by the decoder is, in general, the a posteriori probability. For the Binary Symmetric Channel (BSC) an equivalent distance measure is Hamming distance and for the Additive White Gaussian Noise (AWGN) channel an equivalent distance measure is Euclidean distance. The design of hardware efficient coders and decoders is the subject of coding theory. The primary problem of error correction coding is the development of good codes which are, at the same time, reasonably easy to decode. [Ref. 9: p. 616]

2. Elementary Convolutional Coding Concepts

A convolutional code is similar to a block code in that in the time K binary input symbols are collected, the encoder outputs n binary symbols. In contrast to the block encoder, the mapping of input K-tuples to output n-tuples is not independent from one mapping to the next, that is, the convolutional codes possess memory. The amount of memory varies for different codes and is specified by the constraint length of the code. The constraint length of a convolutional code is equal to the number of output n-tuple which are influenced by the particular input k-tuple.

71

3. Random Coding Bounds

All the discussion about forward error correction codes has been directed to the performance evaluation of specific codes. In the initial stages of spread spectrum system design, it is useful to know whether any error correction code at all will have adequate power to satisfy system specifications. It is also helpful to have a preliminary idea of the complexity of the code required to satisfy system specifications. Both of these issues can be addressed using the concept or random coding error probability bounds first derived by Shannon. In his classic paper, Shannon proved that error correction coding schemes exist which permit digital communications at arbitrarily low bit error probability provided the transmission rate is below channel capacity.

A key element in this work is the coding theorem, which gives an upper bound on the achievable error probability using forward error correction maximum-likelihood decoding. For a discrete memoryless channel defined by a transition probability matrix $p(y/x)$ and block coding, the probability of a bit error $\overline{P}_{Be}$ averaged over all possible block codes is bounded by

$$\overline{P}_{Be} < 2^{-n(R_0 - R)} \qquad \text{[Eqn. 4.6]}$$

where n is the code block length, R is the code rate in bits per channel use, and R_0 is called the computational cutoff rate. Thus, when $R < R_0$, the bit error probability can be made arbitrarily small by choosing the block length n to be sufficiently large.

A similar result is valid for time - varying convolutional codes. In particular, for binary rate $R = 1/n$ time-varying convolutional codes, the bit error probability averaged over all possible codes is bounded by

72

$$P_{Be} < 2^{-vR_0}/R/[1-2^{-[(R_0/R)-1]}]^2 \quad R<R_0 \qquad [Eqn. 4.7]$$

where v is the constraint length of the code. Thus, for a fixed code rate R and channel cutoff rate R_0, the bit error probability can be made arbitrarily small by making the code constraint length sufficiently large. Observe that convolutional code constraint length plays the same role in equation 4.7 that block length played in equation 4.6. [Ref.9]

V. ASSESSMENT OF FREQUENCY BANDS USED FOR SPREAD SPECTRUM SYSTEMS

A. INTRODUCTION

Since military spread spectrum systems are designed primarily for:

1. Low probability of intercept.
2. Antijam capability and
3. Cryptographic capabilities,

it is possible that military planning for spread spectrum use may ignore the frequency allocation tables and consider only the tradeoffs involved in frequency use during tactical situations.

However, any new system being developed must meet certain requirements, both during the developing cycle and in peacetime training and readiness operations, including compliance with frequency allocation rules. Because the international and national radio regulations do not currently address spread spectrum systems, existing national and international notification, coordination and registration procedures should be followed to obtain recognition and protection at all levels. At the international level, the International Telecommunication Union (ITU) in Geneva, Switzerland, provides the forum for the coordination of spectrum users. The U.S proposals to date on most of the spectrum are contained in the 5th Notice of Inquiry (NOI) released by the U.S Federal Communications Commission (FCC). Some of the uses currently being debated nationally and internationally include the accomodation of new spread spectrum systems that can share with the classical ''narrow-band'' systems. [Ref. 16]

74

To facilitate the authorization process and insure that spectrum compatibility exists at a particular location, an Electromagnetic Compatibility (EMC) analysis is required. This analysis should consider co-site, intersite and adjacent channel and band operations within the common electromagnetic environment. This necessity for compliance must be adhered to if the goal of spread spectrum acceptance among international and national users is to be achieved. Without their acceptance, the use of spread spectrum systems would be delayed until they are designed and developed in such a manner as to be consistent with the allocation tables and radio regulations.

The identification of frequency bands that can be used by spread spectrum systems requires consideration of a number of factors, including frequency allocation regulations, present usage of the spectrum, possible tactical usage and the possible variations in spread spectrum systems design.

The main substance of the Final Acts of the World Administative Radio Conference 1979 (WARC-79) in Geneva, Switzerland, is the allocation of frequency bands to the various services such as broadcasting, maritime mobile, etc., in different regions of the world, together with technical regulations for the use of frequencies and intricate procedures for notification and coordination of frequency assignments to establish the right to international protection from harmful interference. There are also operational provisions for certain services, and finally, a compendium of resolutions and recommendations to guide planning, progressive changes in spectrum utilization, and studies for future development. In addition to the allocation of the spectrum service, national frequency allocation rules define the type of user allowed in each band as goverment user or non-goverment user.

National frequency allocation rules also define the channelization of each band (the frequency separation required between users) and the maximum allowable bandwidth.

B.   SPREAD SPECTRUM IMPACT ON SPECTRUM UTILIZATION

The choice of spread spectrum technique may appear strange when the assumed goal of radio regulations is to conserve the frequency spectrum and certainly not use more bandwidth than necessary. Radio regulations tried to keep signals within the radio frequency enviroment separated by assigning each signal to an allocated frequency slot. However, there are other methods of separating signals, or in the general case, information sources. Consider the difference between Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). The FDMA system is the simplest of all existing multi-access systems as it uses only traditional frequency division multiplexing hardware. The commercial satellites Intelsat I through Intelsat IV and all traffic control units use FDMA systems and many military satellites are still FDMA. The disadvantage of the FDMA systems is that the system capacity is limited by the intermodulation in the satellite repeater. The total capacity undergoes a rapid drop between one and four accesses. In view of this disadvantage, the Intelsat V, and U.S.A military systems among others are switching to TDMA systems. In TDMA systems,each information source, after being digitized, is assigned a time slot. As the number of uses increases, TDMA systems perform much better than FDMA systems. In TDMA systems analog messages have to be digitalized and the messages are transmitted in bursts which require buffer storage, unique word detection, and burst synchronization.

As a result of spread spectrum techniques developed over the years, a third signal multiplexing technique, called Code Division Multiple Access (CDMA) can be identified. In this technique, both time and frequency are utilized.

Using CDMA many information channels can be established in the same frequency channel and at the same time, without interference between channels. CDMA may be the most promising spread spectrum technique because it allows implementation of a multiple access system in which many users can share the same channel in an unsynchronized way, with each user being assigned a different pseudorandom code. Also, with CDMA, more importantly, repeater bandwidth of a satellite is utilized efficiently and no guard bands are inserted, and it provides simultaneous ranging with telephone communication.

However, the use of spread spectrum systems almost invariably introduces complications in frequency management It is usually impossible to coordinate frequency band utilization among transmitters to provide a clear broadband channel for the communication function.

There are numerous operational advantages for spread spectrum that, taken together, impact on spectrum utilization. Some of these advantages are [Ref. 17: p. 36]:

1. The use of a large number of frequencies in the waveform results in a form of frequency diversity that significantly reduces the degradation in performance that normally arises from rapid fading.

2. Any user can access the system anytime without waiting for a free channel.

3. There is no hard limit on the number of active users that can be handled simultaneously by the system. When the number of users exceeds the design value, the result is a degradation of performance for all users rather than denial of access.

4. Since all users occupy the same band, all user hardware is identical except for the filters associated with the unique signal set.

77

5. Under circumstances in which the full capacity of the system is not required, spread spectrum systems may coexist in the same frequency band as conventional narrowband systems without excessive mutual interference.

At this time the results are inconclusive and incomplete on how spread spectrum systems will impact on spectrum utilization. However, the numerous operational advantages, the more uniform and higher quality performance and the ability to capitalize upon technological advances leads to the conclusion that such systems are serious contenders for the communication system of the future.

C. FREQUENCY BAND SELECTION

The use of radio telecommunications have grown enormously in the past few decades to provide a broad range of services required by modern civilization. One consequence of this growth is that portions of the radio spectrum are very crowded with users, there is a requirement to meet legitimate needs of still more users. This presents major problems to members of the ITU and national spectrum managers in developing procedures for sharing, allocating, and assigning the spectrum so as to accomodate even more use of the spectrum.

One possibility of alleviating some of the demands for spectrum is, to move to ever higher frequencies where there is less, or no, current usage. However, use of those higher frequencies may not permit the kind of system performance required, or equipment and techniques for operating at higher frequencies may not exist or are too costly for the service required. Also, frequency management above 40 GHz after WARC-79 will require of the frequency manager a much more extensive understanding of telecommunications, basic technology, and technology trends than has

been required in the past when making frequency assignments at the lower frequencies. This knowledge is required not only to assess the priority of requirements but also to be able to predict impending requirements. This understanding and its application are essential if frequency management is to follow the general philosophy laid down by WARC-79 and embodied in the frequency allocations above 40 GHz: allocations and frequency asignments should fulfill requirements and, above all, stimulate rather than discourage use. Using his knowledge of technology, the frequency manager should guide use into the most profitable bands. The probabilistic nature of interference becomes a paramount importance in the above 40 GHz region, because of the highly variable nature of the environment and its large effect on propagation, and because of the potential for narrow antenna beams. The frequency manager must develop tools to take into account the highly probabilistic nature of interference in making frequency assignments and carrying out his duty as a frequency manager. Thus, other solutions must be found.

The principal one employed today is that of reducing the bandwidth used to provide a service, either as a result of improved techniques for reducing necessary bandwidth or a forced reduction of assigned bandwidth administrative decision. Reducing assigned bandwidth also has obvious limitations, for the bandwidth assigned cannot continually be reduced without degrading system performance quality or requiring more costly equipment.

Another solution which may permit an overlay of more users in a given band of the spectrum is the spread spectrum technique. The spectra have little resemblance to those of conventional modulation schemes. However, spread spectrum techniques, through the properties of coded modulation, can provide systems which produce low

interference to other systems, have high interference rejection capability, provide multiple access capability, and have other useful capabilities.

A spread spectrum system which is designed for low-density use, can be introduced into bands used by many types of conventional equipment if proper coordination techniques are used. Antenna discrimination, physical siting and power programming can be used to ensure that a low-density spread spectrum system will be compatible with conventional narrowband systems in the same frequency band. Since frequency band usage can be categorized by type of user, frequency band selection for spread spectrum systems can be aided by knowing the spread spectrum design constraints and the electromagnetic compatibility within each category of user equipment. The design constraints can be determined by analyzing the electromagnetic compatibility of several types of spread spectrum systems with typical users, thus providing a relative measure of electromagnetic compatibility between the various types of spread spectrum equipment and conventional equipment.

The standard for comparison is the distance separation required between the spread spectrum system and the equipment in each functional category of conventional equipments, thus giving an indication of the ability of the equipments to operate in the same geographical area as the spread spectrum methods.

A generalized frequency band can be identified by the military spread spectrum system designer, based on such restrictions as component availability, power and propagation. Frequency allocation tables can be used to select candidate bands, based on the service of the spread spectrum equipment and on the fact that the system should be government operated. To determine the frequency bands that will be compatible with spread spectrum systems, an

electromagnetic compatibility analysis with present band
users must be considered in detail by analyzing the
possible interference effects of the systems (spread
spectrum and conventional). Obviously, this must be resolved
before the communication community will accept wide-scale
use of spread spectrum systems.

D. RADIO SPECTRUM UTILIZATION

1. Introduction

The Administrative Radio Conference of Cairo (1938)
in it's decisions, recommended that frequencies be used in
accordance with the ''Table of Frequency Distribution'' and
frequency assignments were published for information only
in a service document called the ''Frequency List''. The
administrative frequency assignments with the table are
compulsory, and by according frequency registations in the
''Master International Frequency Register'' a certain
juridical value in order to fix the reciprocal rights of
obligations, for various countries, deriving from the use
of a frequency by one country for a clearly defined
purpose. The keystone of these procedures is the findings
based on the results of an assessment of the probabilities
of interference made at the time a new station is put into
service or when the characteristics of an existing station
are changed. These findings are issued by the international
body, the Iternational Frequency Registration Board (IFRB)
of the ITU. One of the main duties of the Board, whose
functions are described in detail in Article 8 of the Radio
Regulations is assisting administrations in the field or
radio spectrum utilization. In 1951, radio conference
procedures were developed and in 1959 the functions and
activities of the IFRB are extended, as a result, the IFRB
is now able to play significant part in affective frequency
management.

81

The assistance the IFRB gives to administations is mostly direct in nature where the Board studies, if necessary with the help of other administrations, the special requirements of an individual country for one or more radio frequencies to meet its specific telecommunication requirement. The Administrative Radio Conference, Geneva 1959, adopted a recommendation inviting the IFRB "to provide administrations of countries in need of special assistance with the necessary information and technical data, including the detailed explanation of the radio regulations, which will permit these countries to choose and obtain proper frequency assignments for their operations.'' The purpose of this recommendation is illustrated by a number of provisions introduced into the Radio Regulations. Under these provisions the Board shall conduct a study of the following problems of frequency utilization. [Ref. 18] :

1. Looking for alternative frequencies to avoid probable harmful interference.

2. Searching additional frequencies within a specified portion of the radio spectrum.

3. Cases where two or more frequencies in the same megahertz order are not used due to harmful interference.

4. Alleged contravention or nonobservance of the Radio Regulations or harmful interference.

5. Computation of the increases in noise temperature in some systems, preparation of diagrams showing coordination areas or any other assistance of a technical nature to complete the procedures of coordination, notification and recording in the Master International Frequency Register of Frequency Assignment to Radio Astronomy and Space Radiocommunication Stations.

2. Spread Spectrum Utilization

Although spread spectrum communication systems have been widely studied and used for specialized application, they are not usually considered to be efficient from the

stand-point of spectrum utilization. However, when informa-
tion theory is used to compare the number of simultaneous,
compatible users of a finite segment of the spectrum which
could be supported under two different operational schemes
(narrowband and wideband) the results suggest that wide
band or spread spectrum may enjoy a great advantage with
respect to a narrowband system in terms of spectrum
utilization theory.

One concern which ligitimately arises is whether
a multiple number of spread spectrum users transmitting on
the same nominal carrier frequency and occupying the same
RF bandwidth permits as many total users of that band as
conventional frequency division channeling. A universal
response to this question does not seem possible because
the relative number of users that can be obtained by either
approach depends upon the model assumed for user, signal
power distribution, message length distribution, and
characteristic of equipment used.

The approach of determining how many spread
spectrum users can simultaneously occupy a given band is
based upon the jamming margin of the system. This jamming
margin is that quantity that is usually intended in the
specification of spread spectrum systems, but it is less
readily predicted from bandwidth and information-rate
information. One can be sure, however, that jamming margin
in any given system is always less than the process gain
availiable from that system. Jamming margin (M_j) takes into
account the requirement for a useful system output signal-
to-noise ratio or signal-to-interference ratio and allows
for internal losses. [Ref. 2: p. 10]. The equation for the
jamming margin is:

$$M_j = G_p - L_{sys} - (S/I)_{out} \qquad \text{(Eqn. 5.1)}$$

where

G_p = the spread spectrum process gain
[G_p = (S/I)$_{out}$/(S/I)$_{in}$]

L_{sys} = the system implementation loss, and

(S/I)$_{out}$ = the operationally required ratio at the information output.

For example if the spread spectrum bandwidth is 1000 times that of the information bandwidth, so that G_p = 30 dB, and if (S/I)$_{out}$ is required to be 10 dB and L_{sys} is taken as 2 dB, then the jamming margin

$$M_j = 30-2-10 = 18 \text{ dB}$$

Under the assumption in this example, interference power could not exceed the wanted signal power more than 18 dB and still maintain desired performance. After some arithmetic manipulation, it can be shown that the interference at the receiver input is

$$I_{in \ max} = M + I + S \quad (\text{dB}) \qquad (\text{Eqn. 5.2})$$

where its quantity is in decibels referenced to a common power level base. Unfortunately, Equation 5.2 provides no information about the number of users possible, for the interference shown there could come from 1000 signals of a given level, 100 signals at ten times that level, or ten signals at 100 times that power level. In general, we can observe that the process is such that

$$10 \log \sum_{in} = I_{in \ max} \quad (\text{dB})$$

84

where in is the interference contribution in watts from
each of the n users. For a given situation, there will be
some distribution for in, analytic or otherwise, and the
problem is to find n such that the interference
contributions from the n users sum up to the $I_{in\ max}$ value,
which gives the number of users allowed. For analytical
studies, the distribution of in could be assumed as a
Poisson, chi-squared, Gaussian, or any other statistical
distribution which approximates the situation being
analyzed and, after proper evaluation of the cumulative
distribution values, n could be found for the assumed
interference distribution. As an example, if we use a
mathematically convenient, but unlikely, distribution, that
the same amount of interference is produced at each
receiver by each user transmitter, so that in = c, then,

$$10\log \sum in \ = \ 10\log\ nc\ =\ I_{in\ max}$$

Because for the assumed interference distribution the value
of c must be the same as the value of the wanted signal:

$$10\log n = M + L = G_p - (S/I)_{out}$$

Thus, if we were to consider a system using a 3 KHz
information bandwidth, a 1.5 Mbit/s spreading code rate (RF
bandwidth = 3 MHz), giving a G_p = 30 dB, and a required
$(S/I)_{out}$ = 10 dB, then

$$10\ \log n = 30 - 10\ = 20$$

and

$$n = 1000\ users.$$

Because there are 1000 3 KHz channels possible in the 3 MHz bandwidth, this would represent poor spectrum use efficiency. [Ref. 10: p. 29]

In conventional allocation of a single channel to a single user, a much larger percentage of the 1000 channels would normally be made available to users, the exact number being dependent upon how much spectrum is used to provide protection from equipment characteristics which cause interference over a band of frequencies wider than the required information bandwidth. The reason for the low efficiency of spectrum use in this illustrative case is the tacit assumption that users were on all the time, or at least with a high duty cycle. And, for such cases, band-width expansion systems are usually not spectrum use efficient. However for operations in which a number of stations must be permitted to transmit at any given time, but where each station is only transmitting a fraction of the total time, wideband systems provide greater communica-tion capacity and spectrum utilization than do narrowband systems. [Ref. 10: p. 29]

In a congested band operation, in which a service is assigned various bands of frequencies and users are permitted to operate at any frequency within the band, the communication capacity using broadband systems exceeds that of a narrowband system by

$$C_B = C_N [1/a(S/N)_{min}] \qquad (Eqn. 5.3)$$

where

a = average fraction of time each station is actually transmitting.

$(S/N)_{min}$ = least favorable signal-to-noise ratio anticipated in the narrowband system, and

C_B, C_N = channel capacity per circuit in broadband and narrowband operation respectively.

86

From Equation 5.3 it can be observed that as the number of users increases in a congested band operation, so that the S/N decreases, or as the duty cycle of operation decreases, broadband systems show increasing superiority over narrowband ones. Thus in an environment in which all users operated only on an assigned frequency, a similar relation existed and that low duty cycle operation broadband systems give greater communication capacity for a given bandwidth allocated to the service. The reason for this is that at low duty cycle, the narrowband system wastes spectrum because most of the allocated channels in the band will be idle at any one time. This cannot be avoided since each station must have access to communications at any time. The narrowband allocation eliminates interference between users, while in the broadband case, each station appears as ''noise'' to the others. The broadband system takes advantage of the low duty cycle which keeps the ''noise'' level low and increases the per-circuit capacity. At high duty cycles, the narrowband system results in superior spectrum utilization, and it obviously makes sense to allocate spectrum using the conventional frequency division method for high duty systems, such as broadcast. For low duty rate operations, such as those that occur in mobile systems, systems in which a large number of users rely upon a common relay point, or systems which permit many users to operate on any of a number of frequencies in a band (amateur, Citizen's Band radio, etc.), bandwidth-expanding systems can easily prove to be the more efficient users of the spectrum. [Ref. 10: p. 29]

VI. POSSIBLE APPLICATION OF SPREAD SPECTRUM PRINCIPLES IN SPECTRUM ALLOCATION

A. INTRODUCTION

Spectrum management is an important activity that facilitates the orderly use of the electromagnetic spectrum for many telecommunications and other applications. Most readers are aware of the broad, vital, and growing role which radio communications services play in meeting the domestic and worldwide needs of our modern society in commerce, public safety, defence, education, transportation, and entertainment. While the electromagnetic spectrum is a renewable resource (unlike our energy reserves), the worldwide demand for expanding wireless communications of all types has resulted in competition among the 40 radio-communication services for spectrum and the geostationary orbit space. This competition takes place both nationally and internationally. Although there are common interest areas, the aspirations, expectations, and need of the countries of the world for telecommunications are widely different. Political, economic, and social tensions and pressures are at work in the allocation and use of the spectrum. Radio-wave propagation does not respect international boundaries, and this compounds those tensions and pressures and increases the need for cooperation and sharing. Consequently, because the allocation of the spectrum and its management affects the structure and development of international communications and each nation's system of telecommunications, global collaboration and cooperation based upon technically sound negotiations are essential ifthe chaos of independent, conflicting users is

to be avoided and mankind is to benefit. With these
motivations, approximately 2000 delegates, representing
142 countries, met in Geneva for about three months in late
1979 under the auspices of the ITU to revise the regula-
tions governing the use of the electromagnetic spectrum and
the geostationary orbit. The results of that conference
will have a wide-ranging impact on telecommunications all
over the world on into the 21st Century. [Ref. 19]

The propagation characteristics of electromanetic
energy are such that the allocation of the radio spectrum
must be coordinated at the international as well as
national level. Coordination at the international level is
acomplished through the ITU. The member nations of the ITU
negotiate an international allocation of the spectrum which
by common assent, establishes the basic rules for sub-
sequent national allocation.

Responsibility for national spectrum allocation in the
United States is divided between the Federal Communications
Commission (FCC) and the President. One of the most impor-
tant responsibilities delegated to the FCC by the Communi-
cations Act of 1934 is the management of the non-government
portion of the electromagnetic spectrum. This includes
responsibility for allocation, assignment, and efficient
use of the spectrum. To avoid confusion, it should be noted
that the terms ''allocation'' and ''assignment'' have
rather special meaning in spectrum management. Allocation
is the commitment of bands or blocks of frequencies to the
use of a specific radio service or services. Assignment
includes selecting and authorizing (licensing) the use of
discrete frequencies by individual radio stations within a
service. [Ref. 20 : p 182]

Allocation requires coordination with many entities,
public and private, at both national and international
levels. After a portion of the spectrum has been allocated

89

to a radio service (or services in the case of shared allocations), assignment must be made to specific radio stations within the service. This may be a relatively straightforward process (for example, licensing an amateur station), or it may involve a complex lengthy proceeding, such as a broadcast station assignment when there is more than one applicant or a license renewal is challenged. Efficient use of the spectrum is fostered by promulgation of operating rules and standards, which can also generate controversy and result in extended proceedings.

The FCC is responsible for allocation to all non-federal government radio users, including state and local governments. The Communication Act of 1934 explicitly assigned authority over spectrum allocation for all federal government radio users to the President. Since 1970, this authority has been delegated to the Director of the Office of Telecommunications Policy (OTP). The director of the OTP, exercises this delegated authority primarily through the activities of the Interdepartment Radio Advisory Committee (IRAC). The IRAC consists of representatives of all federal departments and agencies that make extensive use of radio communications. The IRAC serves in an advisory capacity to the director of OTP, and assists the director in all matters pertaining to spectrum management, including allocation.

B.   FREQUENCY BAND SHARING
Spread-spectrum techniques have been developed in the past to permit communication of message information under difficult conditions of very low signal-to-noise ratio (such as may be encountered due to high co - channel interference), low signal levels (such as may occur in systems using very long paths, as, for example, deep space

90

probes), or transmissions having low detectability. They were not developed with a primary objective of spectrum use improvement, and yet the objectives for which they were developed would appear to be desirable for spectrum allocation considerations. Two strategies for employing spread spectrum techniques would seem to warrant further consideration, and experimental verification as to their usefulness for increasing spectrum use efficiency and providing more users satisfactory system perfomance.

One strategy would be to overlay wideband spread spectrum users in selected frequency bands now assigned for a number of narrowband users, and to use the frequencies simultaneously by both kinds of users. Under the right conditions, such simultaneous use of frequencies should be quite practical. The burden of achieving and demonstrating practicality would probably fall on spread spectrum users because most of the spectrum in use today is already filled with narrowband users, traditionally, new users of the spectrum carry the burden of establishing a sharing capability. An approach to this would be to let present users continue operating as they are today and begin building an overlay of spread spectrum users on the present networks. The spread spectrum users would be expected, and likely required, to develop their systems so as to create minimum interference to the conventional systems as well as being able to provide satisfactory operational performance of the spread spectrum systems in the presence of many interesting signals. That this strategy should be practical seems implicit, since the spread spectrum signal is a low density signal (inherent because the signal power is spread over a wide bandwidth) which appears to be incoherent and to the conventional system is viewed as only a small noise increase. [Ref. 10 : p. 28]

91

As an illustration, consider a direct code modulation system using a spectrum spreading code with a rate of, say, 1.5 Mbits/s. It would have a bandwidth between nulls of 3 MHz, and the power of the transmitter is spread over this bandwidth. In that 3 MHz, a 10 W transmitter, say, would average a power density of approximately 3.3 μ W/Hz. Thus, this 10 W signal would have about the same affect in a receiver of 3 KHz bandwidth as would a 10 mW transmitter concentrating its power in a 3 KHz, or less, bandwidth. So, everyone can see that properly designed spread spectrum systems should result in minimal interference in existing narrowband systems.

Additionally, the requirement that the spread spectrum system be able to operate in the existing interference enviroment also seems implicit because of its inherent capability to provide interference rejection that is probably not matched in any other way. As discussed earlier, interference is rejected by the spread spectrum receiver up to some margin level which is a function of the code sequence rate in a direct sequence system, the number of frequency channels used in a frequency-hopping system, or in the compression ratio of a chirp system.

The main obstacle to the development of this strategy of overlaying spread spectrum wide-bandwidth signals on existing narrowband systems will be the reluctance of those currently authorized frequencies to want to share them when they appear to have nothing to gain. The best argument against this attitude is that the world society as a whole needs and will benefit from increasing communication capability. And to achieve that capability, careful planning, cooperation, and spectrum sharing on the part of all will be needed.

C. SPREAD SPECTRUM BAND ALLOCATION

The second strategy, which is suggested for possible application of spread spectrum principles to spectrum sharing, is to establish certain bands for spread spectrum systems and, conceptionally, assign orthogonal codes rather than frequencies channels.

One possibility for accommodating dedicated spectrum assignment and of alleviating some of the demand for the spectrum is to move to higher frequencies where there is less, or no, current usage. If systems can be designed to utilize frequencies above 40 GHz and handle the propagation effects at these higher frequencies, the bandwidth available for radio transmission will become several times the total of that used today. There are some striking differences between the approach to allocation above and below 40 GHz. For example, there are no bands allocated exclusively. This reflects the characteristics of propagation and the small antenna bandwidths achievable at these frequencies, both of which mitigate against interference and make possible sharing situations not possible at the lower frequencies.

The major feature of the spectrum above 40 GHz is the frequency-dependent structure of atmospheric propagation. Propagation for a spread spectrum signal is much the same for any other signal, with the exception that the wide bandwidths employed sometimes restrict system use. The wideband modulation that can cause a system to be restricted in some areas can be a boon in others [Ref. 2: p.272]. The region, above 40 GHz, is characterized by windows, which are bands of relatively low attenuation, and absorption bands, where attenuation is very high. The atmospheric propagation characteristics provide both advantages and disadvantages. Advantages result from the reduced possibilities of interference between the various services and, thus, increased sharing of the spectrum. The disadvantages, of course, are the

93

generally higher atmospheric attenuation and the increased attenuation caused by precipitation. This necessitates considerably more power than is required at the lower frequencies and reduces the reliability of operation. For the purposes of allocation and selection, the spectrum may be divided into bands corresponding to windows and absorption bands due to propagation effects. These are defined primarily by the absorption characteristics of oxygen and water vapor at these frequencies. Of course, the detailed band shapes, center frequencies, etc., will be affected by hydrometeors such as rain and snow. Such effects should be taken into account when performing actual system design and selecting operating frequencies. [Ref. 21: p. 1137]

This strategy could be implemented in an evolutionary manner, as an outgrowth of the first strategy, if, because of their advantages, the number of spread spectra overlaid in a band grew as narrowband systems diminished. Alternatively, when advantages of spread-spectrum techniques become more widely recognized, decisions could be made to implement spread spectrum systems in certain bands with code assignments, as suggested. [Ref. 10 : p. 28]

D.   CONCLUSIONS

The philosophy of spectrum allocation which has existed for many years has been one of sharing the inherent capacity of the radio spectrum among users by frequency division. As the number of users increased, methods were found to reduce the necessary bandwidth so that new users could be accommodated in the spectrum. As user population continues to increase, it can be questioned as to whether frequency division allocation can continue to be the only way of allocating the spectrum, because this approach may not always be the most efficient way of using spectrum.

94

The historical philosophy of spectrum allocation appears to have been based upon the way in which the radio art developed (in particullar, the frequency selective filter), rather than any fundamental physical principle. There are other ways in which the communication capacity of the spectrum can be shared. Frequency division represents a very poor choice for many applications if improvement in the direction of maximization of communication capacity in a given segment of the spectrum is an objective. Application of spread spectrum principles is one way. For if development of solid - state microcircuits, digital techniques, coding theory, and other hardware and software capabilities did not exist at their current level, any suggestion of using spread spectrum principles for spectrum utilization improvement would be meaningless. But because these advances have been made and are having impact upon the trend of system development (e.g., the trend toward digital systems), and because of the advancing demand for increased communications, it behooves the telecommunications community to reexamine the methods of spectrum sharing and to determine in light of current capabilities whether modification of the present method is not both necessary and desirable. if the benefits of communications to the world's society are to be maintained. [Ref. 10 : p. 30]

Two approaches have been proposed for accommodating spread spectrum systems in the frequency spectrum. One approach is to overlay wideband spread spectrum users in selected frequency bands now used for a number of narrowband users and to use the frequencies simultaneously by both kinds of users. The second approach is to establish certain bands exclusively for spread spectrum systems and to assign orthogonal codes.

In practice, the band sharing approach between spread spectrum systems and conventional systems is preferred

over the allocation of a few specific bands for spread spectrum systems, based on a realistic appraisal of the likelihood of obtaining internationally and nationally acceptable frequency bands. Frequency band sharing between spread spectrum systems and conventional systems is possible in a number of frequency ranges if spread spectrum system design characteristics are properly controlled.

The dedicated band approach appears to be less desirable at this time from a military viewpoint because of the possibility of jammer concentration in the selected bands. However, it may be a feasible long term solution for accommodating spread spectrum systems as technology improves. Therefore, the concept of allocating dedicated frequency bands for spread spectrum systems use should not be pursued at this time.

Thus, based on a realistic appraisal of obtaining international and national acceptance, band sharing between spread spectrum systems and conventional systems is preferred, while selected frequency bands could become an outgrowth or end result from the first strategy.

VII. <u>SUMMARY AND CONCLUSION</u>

Led by the Global Positioning System (GPS) and the Joint Tactical Information Distribution System (JTIDS), the spread spectrum concept has emerged from its cloak of secrecy. And yet the history of this robust military communication technique remains largely unknown to the modern communication engineer.

Spread spectrum systems, because of the nature of their signal characteristics, have at least nine (9) important performance attributes. The advantages of using spread spectrum signals instead of conventional narrowband signals or other wideband signals include the following:

1. Processing Gain,
2. Jamming Resistance,
3. Traffic Privacy,
4. Low Probability of Intercept,
5. Multiple Access Capability,
6. High Resolution Ranging Capability,
7. Short Synchronization Acquisition Time,
8. Multipath Rejection and
9. Near-Far Performance.

The Processing Gain achievable by demodulating or decoding a spread spectrum signal is equal to the ratio of the RF bandwidth to the information data rate, or traffic signaling speed. The processing gain for these signals is:

$$\text{Processing Gain} = G_p = \text{RF bandwidth} / \text{Data Rate or Information Rate}$$

Spread spectrum systems generally possess a large processing gain which allows these systems to operate with a low

97

signal-to-noise ratio at the input of the receiver. Such a high processing gain allows the signal to be received below the level of the noise and still provide reliable communications.

The Jamming Resistance of the Hybrid FH/DS is generally better than that achievable by using either the frequency hop or a direct sequence signal by itself. The frequency hop modulation decreases the effect of a single frequency jammer by hopping to numerous frequencies and thereby reducing the time that the jammer frequency matches the hybrid signal frequency. However, to further reduce the effects of narrowband jammers, frequency hop systems usually incorporate error - correcting codes for information transmission. Even though some bits are received incorrectly due to the jammer, the errors can be corrected when the information is decoded. The effect of the jammer is further reduced by the direct sequence modulation. Even when the jammer frequency corresponds to the hybrid signal frequency during a single hop period, the demodulation process of the direct sequence portion of the signal spreads the jammer power over a wide bandwidth. By filtering the output of the decoder, the narrowband traffic is retained while most of the jamming signal power is filtered out. Therefore, the decoding process recovers the desired traffic while rejecting the jamming signal.

Spread spectrum systems provide some Traffic Privacy. Direct sequence signals can provide some degree of security. Through the use of non - linear spreading codes, detection and demodulation of this type of signal can become extremely difficult and in some cases, impossible. Non-linear sequences cannot be recognized and reconstucted this easily. Even when many consecutive code elements are detected, prediction of the entire code is virtually impossible. Non-linear codes are also generally very long

so that the code does not repeat during the transmission of the traffic. Frequency hop systems provide some traffic privacy. The low probability of intercept combined with pseudorandom frequency hopping make these signals difficult to demodulate for unintended receivers. However, if traffic security is desired, the traffic must be encrypted because the frequency hopping modulation does not provide any traffic security.

Since the spread spectrum signal power is spread over a wide bandwidth, the power density (the power in a 1 Hz bandwidth) is extremely low. Therefore, when intercepting spread spectrum signals, the signal-to-noise ratio at the intercept receiver will probably be very low. The signal may even be below the noise level. The signal frequency spectrum looks like noise and the received signal-to-noise ratio is generally very low. Additionally, in frequency hop signals, the low average power density combined with the pseudorandom frequency hopping pattern make these signals difficult to detect or intercept. Therefore, the probability of intercepting these signals is low.

Numerous users may transmit in the same frequency band by using unique direct sequence or frequency hopping codes. Time division, frequency division and code division multiple access sytems can all employ spread spectrum signals. In the time division multiple access systems, each user is assigned a time slot for transmission. Frequency hop signals along with direct sequence signals and many other signals can be used for time division multiple access systems. Frequency division multiple access systems assign a frequency band for each user. While most frequency division multiple access systems employ narrowband signals, wideband signals could also be used. The code division multiple access systems primarily employ frequency hop, direct sequence, or hybrid spread spectrum signals. The use of

unique direct sequence codes is not as good as using unique frequency hopping codes. Unique frequency hopping codes allow transmission of signals which do not interfere with other receivers. The intended receiver hops in frequency so that it detects only the signals intended for it. Frequency hopping codes which are not unique to a specific receiver never contribute noise to that receiver. By carefully selecting the codes for all the users, the mutual interferance can be minimized. By using error-correcting codes for information encoding, the mutual interference is further reduced.

The precise timing required to synchronize a received direct sequence signal and the receiver replica provide an accurate means of determining the range between two units. When the spreading codes for both units are synchronized, the range from one unit to the second unit can be determined by the time delay between transmission of the direct sequence signal by the first unit and reception of this signal by the second unit. Thus, direct sequence signals can be used to accurately determine the range between units. Many frequency hop systems make no attempt to transmit a coherent signal. The synchronization accuracies required for a noncoherent frequency hopping signal are much less than for a coherent system or a direct sequence system. Therefore, the ranging accuracy for noncoherent systems is poor and generally considered unuseable unless an extremely high hopping rate is used. However, if a coherent frequency hopping system is used, ranging accuracies can approach the accuracies of a direct sequence system. The difficulty encountered in building coherent frequency hop systems often makes the direct sequence systems more advantageous.

Frequency hop systems generally require a significantly shorter time to acquire synchronization than direct

sequence signals having the same bandwidth. In frequency hop systems, the receiver can usually synchronize with the transmitted signal within a small fraction of a second. Direct sequence systems usually require about a second to achieve synchronization. For some applications like voice communications, the shorter acquisition time is highly desirable. If one or two seconds is required for synchronization, the transmitter has to be keyed at least two seconds before the voice will be received at the receiver. Therefore, a voice reply would be delayed by at least two seconds. By using frequency hop signals, the receiver can synchronize within a fraction of a second and no noticeable delay is encountered for voice communications.

When the transmitted signal is propagated towards the receiver, several paths may exist which may cause interference due to phase cancellations at the receiver. This is called multipath propagation. If the signal is propagated via the ionosphere, the path time delays can range from tens of microseconds to several milliseconds. Similar multipath delays can exist at VHF and UHF frequencies due to reflections from buildings, towers and other reflective materials. If the hopping rate is adequately high, then the receiver listens on a new frequency slot before the interfering paths have a chance to interfere with the direct path. For slow frequency hoppers, the path propagation times are too fast to allow the receiver to reject the interference. As long as the delay of the multipath signal is not within one chip period of the direct path spreading code sequence delay, the multipath signal appears as noise and generally does not effect the receiver operation. During initial synchronization, the receiver may lock onto a multipath signal and thereby cause some interference. However, with a proper choice of hop rate and direct sequence coding, this problem can be minimized.

Near-Far Performance describes the behavior of the spread spectrum system with other users both near and far away from the intended users. A frequency hop system jumps to many different carrier frequencies in a time interval and filters the carrier frequency with the intermediate frequency filter. Users outside the filter's bandwidth are rejected and only the proper signal is demedulated. Since the IF filter passes only a narrow bandwidth signal, potential interferers are more easily rejected.

As far as general communications are concerned, applications of spread spectrum techniques are relatively obvious. Some areas in which spread spectrum methods have already been put to good use are:

1. Communications,
2. Command and Control of Remotely Piloted Vehicles.
3. Ranging Systems,
4. Position Location,
5. Multiple Access Systems and
6. Radar Systems.

Key to the continuing growth of radio systems is the availability of radio frequencies which can be used for communications. Without available spectrum, new services may be denied, or forced to operate on frequencies already assigned. As a result of the inevitable increase in interference, existing services may be degraded and the new services will operate less than satisfactorily.

Many difficulties arise from what is termed administrative convenience, which results from the sheer impossibility of making a proper electromagnetic compatibility analysis of the impact of each new request for use of the spectrum on the existing users. As a result, assignment tables or rules based on antiquated data are used as a substitute. Revision of these rules in the light of new knowledge will be a lengthy and difficult process but hopefully it will be accomplished.

102

The radio spectrum is a critical world and national natural resource, essential to the life, security, and defense of the people of each country. The demand for frequencies or channels in certain parts of the spectrum often exceeds the supply. Prudence therefore requires that the spectrum be conserved for the more essential needs. Radio spectrum conservation requires the management, supervision, and regulation of the use of the spectrum in such a manner as to ensure, insofar as practicable, the satisfactory accommodation of present and foreseen frequency requirements for national security and defense, foreign relations, safety-of-life and property, economy, culture, education, and entertainment. It involves consideration of treaties, national policy, national radio-communication needs and their relative importance, and appraisal and judgment of proposed radio operations. The measures taken to conserve the spectrum and to effect sound use thereof, frequently are referred to as ''frequency management.''

The management of this resource has as its goal the accommodation of spectrum users in an orderly and efficient manner. Frequency management is defined as the utilization of scientific knowledge, engineering skills, and administrative procedures to enable a variety of telecommunications systems to share the radio-frequency spectrum without unacceptable interference to any one of them. One of the issues currently being debated nationally and internationally is ''the accommodation of new spread spectrum systems that can share with the classical narrow-band systems.'' Because of its technological characteristics spread spectrum systems offer significant advantages to users, while at the same time, they improve overall spectrum use. For the user, a spread spectrum system can be used to reject narrow-band interference and to permit operations in areas where signal congestion would make communication

using conventional systems impossible. At the same time, if the spread spectrum signal is used intermittently and if it is below the noise threshold of the narrow-band receiver, it will not interfere with the narrow-band user. Spread spectrum is clearly not the best answer to all problems in all circumstances, but in the critical and rapidly changing field of high density communications,it may prove to be the best or possibly the only answer.

Today's successful spectrum manager must combine many talents, including a knowledge of the technical, legal, economic, political, sociological, and even psychological aspects of the businnes. Only part of this can be taught in a classroom, as observed by Vice Admiral J.L. Boyes, U.S. Navy: ''Radio frequency management is done by experts who meld years of experience with a curious blend of regulations, electronics, politics and not a little bit of larceny.'' What he meant is that spectrum managers must justify requirements, horse-trade, coerce, bluff, and gamble with an intuition that cannot be taught other than by experience.

LIST OF REFERENCES

1. Clark, R.L.,''Radio Spectrum Utilization as a National Problem,'' IEEE Transaction on Electromagnetic Compatibility, v. 8, pp. 331-347, December 1965.

2. Dixon, R. C., Spread Spectrum Systems, 2d ed., John Wiley & Sons, Inc., 1984.

3. Sujdak, E. J.Jr., Radio Frequency Spectrum Management. Master Thesis, Naval Postgraduate School, Monterey, California, March 1980.

4. Cowgill, R. M.,''National EMC by Design,''IEEE Transactions on Electromagnetic Compatibility, v. EMC-14. pp. 16-20, February 1972.

5. Minasian, J. R., ''Property Rights in Radiation: An Alternative Approach to Radio Frequency Allocation,'' The Journal of Low and Economics, v. XVIII,April 1975.

6. Williams, V. T. and Collins, M. K., The Radio Spectrum International Allocation and Regulation, Master Thesis Naval Postgraduate School, Monterey, California, March 1979.

7. Couch II, L. W., Digital and Analog Communication Systems, Macmillan Publishing Co., Inc., 1983.

8. Pickholtz, R.L..and others,''Theory of Spread-Spectrum Communications - A Tutorial,'' IEEE Transactions on Communications, v. COM-30, pp. 855-883, May 1982.

9. Ziemer, R. E. and Peterson, R. L., Digital Communications and Spread Spectrum Systems, Macmillan Publishing Co., Inc., 1985.

10. Utlaut, W. F., ''Spread Spectrum - Principles and Possible Application to Spectrum Utilization and Allocation,'' IEEE Communications Society Magazine. September 1978.

11. Viterbi, A. J.,''Spread Spectrum Communications- Myths and Realities,'' IEEE Communications Magazine, May 1979.

12. Mohanty, N. C., ''Spread Spectrum and Time Division Multiple Access Satellite Communications,'' IEEE Transactions on Communications, v. COM-25, pp. 810-814, August 1977.

13. Huth, G. K., ''Optimization of Coded Spread Spectrum System Performance,'' _IEEE Transactions on Communications_, v. COM-25, pp. 763-770, August 1977.

14. Ristenbatt, M. P. and Daws, J. L. Jr., ''Performance Criteria for Spread Spectrum Communications,'' _IEEE Transactions on Communications_, v. COM-25, pp. 756-762, August 1977.

15. Kullstam, P. A.,''Spread Spectrum Performance Analysis in Arbitrary Interference,'' _IEEE Transactions on Communications_, v. COM-25, pp. 848-852, August 1977.

16. Hagn, G. H., ''An Introduction to the IEEE EMC Transactions Special Issue on Spectrum Management,'' _IEEE Transactions on Electromagnetic Compatibility_, v. EMC-19, pp. 157-161, August 1977.

17. Montgomery, R. D., _Spread Spectrum Frequency Management_, Master Thesis, Naval Postgraduate School, Monterey, California, March 1983.

18. Khabiri, M. K., ''International Frequency Registration Board (IFRB) Assistance to Member Countries of the ITU in Matters Relating to Frequency Management,'' _IEEE Transactions on Electromagnetic Compatibility_, v. EMC-19, pp. 179-181, August 1977.

19. Bodson, D., and others, ''Spectrum Management and the 1979 World Administrative Radio Conference,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1085-1087, August 1981.

20. Robinson, J. O., ''Spectrum Allocation and Economic Factors in FCC Spectrum Management,''_IEEE Transactions on Electromagnetic Combatibility_, v. EMC-19, pp. 182-190, August 1977.

21. Katzenstein,W. E., Moore, R. P., and Kimball, H. G., ''Spectrum Allocation Above 40 GHz,''_IEEE Transactions on Communications_, v. COM-29, pp. 1136-1141, August 1981.

.

BIBLIOGRAPHY

Alcuri, L., Mamola, G., and Randazzo, E., ''Signal-to-Noise Ratio in Bandpass Direct-Sequence Spread-Spectrum Modulation Systems,'' _IEEE Transactions on Communications_, v. COM-30, pp. 522-531, March 1982.

Bedrosian, E., ''Spectrum Conservation by Efficient Channel Utilization,''_IEEE Communications Society Magazine_, pp. 20-27, March 1977.

Berry, L. A., ''Spectrum Metrics and Spectrum Efficiency: Proposed Definitions,''_IEEE Transactions on Electromagnetic Compatibility_, v. EMC-19, pp. 254-259, August 1977.

Brown, R. G., and others., _Lines, Waves, and Antennas_, 2d ed., John Wiley & Sons, Inc., 1973.

Cohen, D. J., and Rush, C. M., ''Spectrum Management of the HF Broadcasting Service After WARC-79,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1151-1155, August 1981.

Cook. C. E., _An Introduction to Spread Spectrum Communications - Signal Formats and Processing_, v. II, The Mitre Corporation, 1 July 1976.

Davidovici, S., Milstein, L. B., and Schilling, D. L., ''A New Rabid Acquisition Technique for Direct Sequence Spread-Spectrum Communications,'' _IEEE Transactions on Communications_, v. COM-32, pp. 1161-1168, November 1984.

Devore, W. J., ''Computer - Aided Spread Spectrum Signal Design,'' _IEEE Transactions on Communications_, v. COM-25, pp. 861-866. August 1977.

Eckert, R. P., and Kelly, P. M., ''Implementing Spread Spectrum Technology in the Land Mobile Radio Services,'' _IEEE Transactions on Communications_, v. COM-25, pp. 867-869, August 1977.

Feigleson,H.A.,''Provisions for High Frequency Future Use'' _IEEE Transactions on Communications_, v. COM-29, pp. 1156-1160, August 1981.

Geraniotis, E. A., and Pursley, M.B.,''Performance of Coherent Direct-Sequence Spread-Sprectum Communications Over Specular Multipath Fading Channels,'' _IEEE Transactions on Communications_, v. COM-33, pp. 502-508, June 1985.

Holmes, J. K., and Chen, C. C.,''Acquisition Time Performance of PN Spread-Spectrum Systems,'' _IEEE Transactions on Communications_, v. COM-25, pp. 778-783, August 1977.

Iltis, R. A., and Milstein, L. B.,''Performance Analysis of Narrow-Band Interference Rejection Techniques in DS Spread Spectrum Systems,'' _IEEE Transactions on Communications_, v. COM-32, pp. 1169-1177, November 1984.

Kelleher, J. J.,''Regulatory Procedures and WARC-79,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1114-1119, August 1981.

Kirby, R. C., ''Impact of WARC-79 on the Studies of the International Radio Consultative Committee (CCIR),'' _IEEE Transactions on Communications_, v. COM-29, pp. 1094-1098, August 1981.

Klaus, O., ''The Post-WARC Frequency Situation in Central Europe,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1098-1101, August 1981.

Kochevar, H. J., ''Spread Spectrum Multiple Access Communications Experiment Through a Satellite,'' _IEEE Transactions on Communications_, v. COM-25, pp. 853-856, August 1977.

Kowatsch, M., and Lafferl, J.T.,''A Spread-Spectrum Concept Combining Chirp Modulation and Pseudonoise Coding,'' _IEEE Transactions on Communications_, v. COM-31, pp. 1133-1141, October 1983.

Kusaka, H., and Nishida, F., ''A Spectral Analysis of M-ary Direct Sequence Spread-Spectrum Multiple Access Communication Systems,''_IEEE Transactions on Communications_, v. COM-31, pp. 541-546, April 1983.

Laforgia, D., Luvison, A., and Zingarelli, V., ''Bit Error Rate Evaluation for Spread-Spectrum Multiple-Access Systems,'' _IEEE Transactions on Communications_, v. COM-32, pp. 660-668 June 1984.

Lunayach, R. S., ''Performance of a Direct Sequence Spread-Spectrum System With Long Period and Short Period Code Sequences,''_IEEE Transactions on Communications_, v. COM-31, pp. 412-419, March 1983.

Marsh, H. S., _An Introduction to Spread Spectrum Communications - Basic Principles and Concepts_, v. I, The Mitre Corporation, 1 July 1976.

Milstein, L. B., Gevargiz, J., and Das, P. K.,''Rapid Acquisition for Direct Sequence Spread-Spectrum Communications Using Parallel SAW Convolvers,''IEEE Transactions on Communications, v. COM-33, pp. 593-599, July 1985.

Milstein, L. B., Davidovici, S., and Schilling, D. L.,''The Effect of Multiple-Tone Interfering Signals on a Direct Sequence Spread Spectrum Communication System,'' IEEE Transactions on Communications, v. COM-30, pp. 436-445, March 1982.

Milstein, L. B., and Das, P. K., ''Spread Spectrum Receiver Using Surface Acoustic Wave Technology,'' IEEE Transactions on Communications, v. COM-25, pp 841-847, August 1977.

MIT Lincoln Laboratory Report 388, Output Signal-to-Noise Ratio as a Criterion in Spread-Channel Signaling, by R. Price, 13 May 1965.

Parlow, R. D., ''WARC-79 Changes to the Technical Radio Regulations,''IEEE Transactions on Communications, v. COM-29, pp. 1120-1124, August 1981.

Phillips, P. J., and Sullivan, T. M., ''Techniques for the Management of Frequency Bands Shared Between Terrestrial Stations and Mobile or Transportable Earth Stations,'' IEEE Transactions on Communications, v. COM-29, pp. 1179-1182, August 1981.

Probst, S. E., and Bradley, L. L., ''U.S. Perspectives on the New Allocation Tables,''IEEE Transactions on Communications, v. COM-29, pp. 1111-1114, August 1981.

Pursley, M. B., ''Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication - Part I: System Analysis,'' IEEE Transactions on Communications, v. COM-25, pp. 795-799, August 1977.

Pursley, M. B., and Sarwate, D. V.,''Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication - Part II: Code Sequence Analysis,'' IEEE Transactions on Communications, v. COM-25, pp. 800-802, August 1977.

Polydoros, A., and Weber, C. L.,''A Unified Approach to Serial Search Spread-Spectrum Code Acquisition - Part 1: General Theory - Part 2: A Matched-Filter Receiver,'' IEEE Transactions on Communications, v. COM-32, pp. 542-560, May 1984.

Ricci, F. J., and Schutzer, D., U.S. Military Communications, Computer Science Press, Inc., 1986.

Roden, M. S., _Digital and Data Communication Systems_, Prentice-Hall, Inc., 1982.

Scholtz, R. A., ''The Spread Spectrum Concept,'' _IEEE Transactions on Communications_, v. COM-25, pp. 748-755, August 1977.

Scholtz, R. A., ''The Origins of Spread-Spectrum Communications,'' _IEEE Transactions on Communications_, v. COM-30, pp. 822-826, May 1982.

Shaft, P. D., ''Low-Rate Convolutional Code Applications in Spread-Spectrum Communications,'' _IEEE Transactions on Communications_, v. COM-25, pp. 815-821, August 1977.

Stanford Research Institute Project 2325, _Study of Throughput and Delay of Spread-Spectrum Multiple Access Modes_, by S. C. Fralick and J. K. Leung, April 1974.

Stanley, W. D., _Electronic Communications Systems_, Reston Publishing Co. Inc., 1982.

Stark, W. E., ''Coding for Frequency-Hopped Spread-Spectrum Communication with Partial-Band Interference - Part I: Capacity and Cutoff Rate - Part II: Coded Performance,'' _IEEE Transactions on Communications_, v. COM-33, pp. 1036-1057, October 1985

Tanaka, S., ''WARC Allocation and Some of their Impacts on Japan and in Asia,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1101-1107, August 1981.

Torrieri, D. J., _Principles of Military Communication Systems_, Artech House, Inc., 1981.

Watson, R. T., and Luther, W. A., ''Frequency Tolerances and Spurious Emission Limitations,'' _IEEE Transactions on Communications_, v. COM-29, pp. 1130-1136, August 1981.

Yamada, K., Daikoku, K., and Usui, H., ''Performance of Portable Radio Telephone Using Spread Spectrum,'' _IEEE Transactions on Communications_, v. COM-32, pp. 762-768, July 1984

Yao, K., ''Error Probability of Asynchronous Spread Spectrum Multiple Access Communication Systems,'' _IEEE Transactions on Communications_, v. COM-25, pp. 803-809, August 1977.

Yu-Shuan Yen, and Reudink, D. O., ''Efficient Spectrum Utilization for Mobile Radio Systems Using Space Diversity,'' _IEEE Transactions on Communications_, v. COM-30, pp. 447-455 March 1982.

INITIAL DISTRIBUTION LIST

No. Copies

1. Defense Technical Information Center 2
   Cameron Station
   Alexandria, Virginia 22304-6145

2. Library, Code 0142 2
   Naval Postgraduate School
   Monterey, California 93943-5002

3. Department Chairman, Code 54 1
   Department of Administrative Science
   Naval Postgraduate School
   Monterey, California 93943

4. Professor Thomas J. Brown, Code 62Bb 1
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California 93943

5. Professor Paul M. Carrick, Code 54Ca 1
   Department of Administrative Science
   Naval Postgraduate School
   Monterey, California 93943

6. Professor Carl R. Jones, Code 54Jc 1
   Department of Administrative Science
   Naval Postgraduate School
   Monterey, California 93943

7. LCDR Evangelos Agapiou 1
   SMC 1290
   Naval Postgraduate School
   Monterey, California 93943

8. LCDR Thomas P. Katopodis 6
   Beikou 64 Koukaki
   117 41 Athens
   Greece